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ADVANCED FUSION WELDING PROCESSES,
SOLID STATE JOINING AND A SUCCESSFUL MARRIAGE

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Historically, our technological progress has resulted from the challenging design requirements of advanced aerospace systems which have led to the evolvement of new materials, new applications, and a complementing family of joining processes. Mission profiles for advanced systems continually emphasize the need for the highest possible material strength to weight ratios at the higher speeds over a wide range of temperatures. As these new materials emerge for application their ability to be joined must be determined with processes and techniques developed to permit their practical use. Characterization of the material to be joined, the geometry of the component parts, their thickness and dimension, the required joint properties, and the environment which the assembly must withstand are essential to selecting the joining or fastening process. The technical area of metals joining is recognized as vital to the production of advanced Air Force systems since joints of high integrity with properties approaching those of the parent material are essential for maximum utilization of the required materials.

A sizeable number of joining processes exist some of which are relatively new and are gaining substantial application for meeting the joining requirements of current and future production. The processes are categorized as fusion welding, solid state joining and specialized

combinations an example of which is the weldbond process. This is a resistance spot weld-adhesive bond process working in combination to obtain the benefits of each process. The particular processes selected for discussion herein have gained significant government and industry development and have evolved for production use. These are electron beam welding, plasma arc welding, diffusion bonding, inertia welding, and weldbond.

ELECTRON BEAM WELDING

Electron beam welding is defined in the Welding Handbook as a fusion joining process in which the workpiece is bombarded with a dense stream of high velocity electrons, and virtually all of the kinetic energy of the electrons is transformed into heat on impact. (Reference 1) Electron Beam welding as a fusion process offers the advantages of high depth to width ratios, small heat affected zones, reduced residual stress and distortion. It is conducted in a single pass full penetration mode as opposed to the conventional multi-pass arc welding processes. Electron Beam welding is continually gaining new application for production and has been demonstrated for joining critical structures. North American Aviation made an electron beam close out weld on the wing to stub wing fuselage attachment in the B70 program. Solar Division of International Harvester electron beam welded the rotor hub from 2.250 inches thick Ti-6Al-4V for the Cheyenne Helicopter program. (Figure 1) Solar is also applying electron beam welding to wing flaps and slat tracks on the Lockheed L1011 airplane. Grumman Aerospace Corporation is currently electron beam welding the wing center box of the F-14 airplane from titanium 6Al-4V alloy. (Figure 2)

The Grumman commitment to electron beam weld the F-14 titanium center wing box structure represents the most advanced application of the electron beam welding process to primary critical aircraft structure. The commitment to electron beam weld titanium was based on a significant

weight savings potential (estimated at 50% less than steel). The structure is fabricated from 45 machined parts and the completed assembly has approximately 70 welds all made in a vacuum environment by electron beam welding.

In primary critical aircraft structure, electron beam welding may be considered to offer a certain amount of risk since it is a relatively new process with no previous application to wing carry through structure. It should be noted that the F-111 wing carry through structure of D6ac steel was gas tungsten arc welded by using multi-pass welding techniques. Without belaboring the point, the welded F-111 carry through structure was never determined to be a problem area. The electron beam welding process offers significant advantages over the gas tungsten arc welding process. Electron beam welding advantages of high depth to width ratio, smaller heat affected zones, reduced residual stress and distortion are desirable. The ability to complete a weld in a single pass at reduced heat input, compared with a multi-pass gas tungsten arc weld is a desirable objective.

The electron beam process is not a utopian push button automated process. For successful application to complex structures during the course of fabrication, the process requires a cooperative effort between designers, welding engineers, metallurgists, quality assurance and stress engineers.

Large structures dictate a requirement for large electron beam welding equipment and accompanying large vacuum chambers. (Figures 3 and 4) This necessitates during the welding process that the tooling, fixturing, joint fit up, gun to workpiece alignment and seam tracking must be precise. Since the electron beam process produces a narrow weld (.020 to .060 approx.) joint, fit up must be precise. The possibility of the beam missing the joint exists. In the case of the F-14 Grumman uses what is referred to as a "witness line" technique to assure the desired weld width and penetration. This witness line tech-

nique involves the scribing of lines parallel to the weld joint on both the surface and underside of the joint. The weld is made along the joint in a full penetration pass. Subsequent to welding, the weld is visually inspected to determine if the witness lines are obliterated by the weld bead on both the surface and underbead side. If the lines are wiped out it provides assurance that the joint has been fully penetrated and width of weld is acceptable. This may appear to be a crude seam tracking approach to assure weld width and penetration, but it does work. Other EB seam tracking techniques such as probes riding in or parallel to the joint and depending on transducer correction thru servo controls have not established confidence levels equal to the "witness line" technique.

There are other concerns regarding precautionary measures with the EB process to avoid defects. As in any arc welding process defects can occur. Some of the more significant defects include arc outs, porosity, undercutting and lack of fusion. Arc out (electron beam is extinguished) usually occurs during a welding operation as a result of contamination of the electron beam welding gun components. A special glow discharge cleaning procedure is utilized regularly and is effective in keeping filaments clean for welding. Most arc outs occur when welding at high power inputs or when the beam is operated continuously for long periods of time. Defects caused by arc outs can be repaired in titanium by rewelding with precise control of slope out of the beam.

The foregoing types of defects that may occur in EB welding dictate a requirement for highly reliable nondestructive inspection techniques, for assured quality control. Grumman in their F-14 program has placed major emphasis on nondestructive inspection techniques, including dye penetrant, X-ray, C-Scan ultrasonic techniques and delta ultrasonics. A continued effort is in progress to develop more reliable standards to assist in the interpretation of ultrasonic scan patterns.

In the F-14 program Grumman generated mechanical properties data for the titanium 6Al-4V alloy and titanium 6Al-6V-2Sn. Grumman welded

the titanium alloys by electron beam and gas tungsten arc in varying thicknesses. In general the tensile strengths, elongations, and joint efficiencies of the electron beam welds were better than the gas tungsten arc welds. Tension-tension fatigue properties of EB welds in 0.50 inch Ti 6Al-4V were better than gas tungsten arc welds of the same thickness made in 4 passes with filler wire. Grumman generated a substantial amount of surface flaw crack growth data under constant amplitude for one inch thick EB welded, annealed Titanium 6Al-4V plate. Grumman also conducted F-14 wing spectrum fatigue loading tests on one inch thick Ti-6Al-4V in order to be able to relate fracture toughness variations with flaw growth rate and establish realistic limit loads for structural designs.

An Air Force Materials Laboratory, Manufacturing Technology Division sponsored program is currently in progress at Grumman for evaluation of sliding seal electron beam welding system. (Figure 5) Aluminum 2014-T 651, Titanium 6Al-4V and HY 130 steel in plate thickness have been welded and the capabilities of the sliding seal electron beam welding equipment to produce weldments with quality acceptable for aerospace structure have been determined. (Figure 6)

The sliding seal electron beam welding system was produced by Sciaky Bros. under a previous Air Force contract. It consists of a portable vacuum, moving electron beam welding head that is mounted on a ram manipulator, back up tooling and associated power supply and controls. The power capacity of this unit is 30 kilowatts (60 KV, 500 ma) with vacuum pressures ranging between 1×10^{-4} torr and 100 microns of Hg. This vacuum is obtained by pumping between two nonmetallic seals in the welding head.

Under a recently completed AFML contract at Bell Aerospace electron beam welding of HY 130 steel, D6ac low alloy high strength steel fully heat treated, 9 Ni-4Co-.30C steel, and titanium 6Al-6V-2Sn in a range of thicknesses from 0.125 through 1.0 inches was conducted. The mechanical properties of electron beam welds were comparable to base

metal properties and exceeded the properties of other competing fusion welding processes. (Figure 7)

Electron beam welding will continually gain new applications in large structures built up from smaller segments. The joining of plate materials, smaller forgings and the advantages of the single pass full penetration capability enhances consideration for using the process. The weight reduction realized by eliminating the penalty associated with mechanical fasteners and hole generation in thick plate stimulates consideration of the process for weight critical structures.

PLASMA ARC WELDING

Plasma arc welding is an arc welding process in which the heat is produced by a constricted arc between a nonconsumable electrode and a workpiece (transferred arc), or between a nonconsumable tungsten electrode and a constricting orifice, (nontransferred arc). (Reference 2)

Plasma arc welding is closely related to gas tungsten arc welding. Plasma is present in all arcs. If a constriction containing an orifice is placed around the arc, the amount of ionization, or plasma, is greatly increased. This results in higher arc temperature, a more concentrated heat pattern, and higher arc voltage than can be obtained with a nonconstricted arc.

The plasma arc welding process has evolved in a manner typical of any new joining process considered for aerospace application. The equipment producing industry in recognizing the potentials of the plasma arc torch as an energy source for welding took the lead in designing and marketing plasma arc torches for mechanized welding. The Air Force Materials Laboratory, Manufacturing Technology Division realizing the potentials of the plasma arc process and the relative shortage of data and experience sponsored a program in July 1966 with the Aerojet-General Corporation for a comprehensive process development and evaluation for application to aerospace materials and structures. (Reference 3) Under this initial Air Force sponsored contract Aerojet developed substantial data describing the capabilities of the plasma arc welding process for

making straight-seam and circumferential butt welds in rocket motor cases and other weight-critical pressure vessels. The materials welded in this program were 18% Nickel maraging steel, 9 Nickel-4 Cobalt, and Titanium 6Al-4V over a range of thicknesses from 0.25 inches through 0.62 inches. Aerojet also demonstrated the capability of applying the plasma arc welding process by producing girth welds in six, 24 inch diameter spherical pressure vessels. Three of these spheres were 0.25 inch thick 6Al-4V titanium alloy, and three were 0.50 inch thick 18% Ni 200 KSI grade steel. The welded vessels were nondestructively inspected by visual, dye penetrant, X-ray and ultrasonic techniques. The vessels were heat treated, then hydrostatically pressurized to burst failure. Hydrostatic pressure and related strain gage data were recorded for all tests and acoustical wave emission corresponding to incremental flaw growth were monitored for two burst tests. (Figure 8) The results of this pressure vessel test program verified the plasma arc process potential for producing high quality butt welds reported in previously published literature.

Subsequent to the foregoing contract an AFML program was awarded to Allison Division, GMC, for development of the plasma needle arc process (0.1 to 10.0 amps) for selected thin gage engine materials and applications. (Reference 4) Several alloys were welded including titanium 6Al-4V. The needle arc process is limited to a maximum of approximately 0.030 inches in thickness. Under this contract thin gage engine components including exhaust collector inner cones for the T 63 engine, outer combustion case for the T 63 engine (Figure 9), anti-icing compressor vane for T 56 engine and a compressor arc discharge tube for the T 63 engine were welded. This program resulted in the conclusions that low amperage plasma arc welds are equal to gas tungsten arc welds in respect to weld bead contour and weld travel speed. Welding operators certified to MIL-T-5021 require no training for use of low amperage plasma arc except for brief equipment operation explanation. The pilot arc system enabled the welding operator to initiate the arc in exactly

the desired spot as he is able to see the pilot arc and weld seam through a weld lens before transfer to welding current. This prevented stray arc strikes and marks detrimental to thin material welding. This program resulted in the recommendations that plasma arc welding is an acceptable and advantageous process for joining foil materials up to 0.030 inches in edge, square butt, and flange melt down joints.

In sequel to the plasma needle arc (10 amp) process a program was conducted by the Allison Division, GMC, for a plasma arc process optimization of the Linde 100 ampere low current plasma arc welding process. (Reference 5) Five materials common to gas turbine engines were welded. These included 310 stainless steel, 410 stainless steel, Inco 718, Titanium 6Al-4V and 4130 steel alloys. Included were thicknesses of 0.015 through 0.125 inches. Test panels for manual and machine welding included square butt, edge, lap, and T joints. Single pass, keyhole mode machine welding with the addition of filler material for square butt joints was highly successful for gages of .048 through 0.125 inches. Keyhole mode welding provided assured penetration, significant reduction in weld bead width, lower amperage requirements and higher travel speed. Weld strength mechanical properties showed 100% joint efficiency by uniaxial tensile tests. Microstructures were essentially the same as seen in gas tungsten arc welds. Radiographic and fluorescent penetrant examinations revealed welds essentially free of porosity and completely free of tungsten inclusions. It was concluded from this program that in comparison with gas tungsten arc welding plasma arc offers increased flexibility of operation, assured penetration in the keyhole mode, greater thickness capacity at 100 amps, reduced need for operator skill, improved quality and potential cost savings. Application of this process will definitely render significant benefits in joint designs requiring square butt and edge welds.

With the industry development and the AFML sponsored development discussed above the plasma arc welding process became prioritized

in aerospace company funded joining development programs. The most impressive development and application of the plasma arc welding process for large aircraft structure was conducted by The Boeing Company for SST prototype application. (Reference 6) The inherent characteristics of the plasma arc process were proven to be particularly advantageous in the welding of titanium components for the supersonic transport. The significant advantages of plasma arc over gas tungsten arc and gas metal arc welding were found to be low weld bead width to depth ratio, narrow heat affected zone, less critical preweld cleaning required, considerably less porosity occurrence, less distortion due to lower total heat input, less critical torch to work distance and part fit up requirement, faster welding speed, elimination of tungsten inclusions and electrode deterioration problems. The advantages over the electron beam welding process were found to be substantially lower original equipment cost, better operator visibility, and lower detail part and fabrication costs. Boeing conducted an extensive plasma arc welding development program beginning with a survey and tests of existing welding equipment. Their methodical evaluation included preweld cleaning requirements; evaluation of orifice and tungsten electrode life; relationship of amperage, orifice gas, orifice diameter and electrode diameter to part thickness; orifice to work distance in inches; maximum allowable joint mismatch, root opening and misalignment; weld bead depth to width ratio for keyhole mode welding; maximum allowable torch lead, lag and work angles; and the minimum and maximum thickness weldable in the keyhole mode. As a result of this process evaluation Boeing evolved a plasma arc welding technique for fabricating integrally stiffened wing panels from titanium 6Al-4V approximately twenty-eight (28) feet long. (Figures 10, 11, and 12) The set up involved machining a titanium 6Al-4V plate and leaving a stub where the "L" shaped stiffeners 0.050 to 0.125 inch thick were to be joined. The machined plate with stubs was fixtured in the vertical position. "L" shaped stiffeners were then plasma arc keyhole welded in the downhand position. During initial SST

prototype part fabrication 7000 linear inches of plasma arc weld in 0.125 inch thick stiffeners were produced with no internal defects indicated by X-ray inspection with 2% of thickness definition. The commitment of plasma arc welding for the integrally stiffened panels on SST attests to the high confidence levels for the process.

DIFFUSION BONDING

Diffusion bonding is a solid state process for joining detail parts into integral configurations with a continuous metallurgical structure. (Reference 7) Bonding is accomplished by the application of pressure and heat for a predetermined period of time in an adequate environment. The pressure is applied to establish intimate contact between the detail parts and the heat to activate the migration of items across the interface for a sufficient time cycle to develop a bond. With the use of sufficient heat, pressure and time the bond interface and the zone near the bond become a single homogeneous microstructure. The material near and within the bond interface has mechanical properties equal to the base material with the result that a diffusion bond can be the optimum structural joint. There have been many approaches evaluated to perform the diffusion bonding cycle depending on the type of equipment used to apply the pressure. (Reference 8) These have included bar rolling mills, plate rolling mills, extrusion presses, hydraulic presses such as forging presses or sheet metal presses and resistance seam welding equipment using both spot and wheel electrodes.

Under a program at North American Rockwell an H53 helicopter rotor hub was selected for diffusion bonding. The rotor hub had been made from a forging of titanium 6Al-4V material. The forging weighs about 1000 pounds but the finish machined weight is about 230 pounds. This part has been successfully diffusion bonded. (Figure 13) Two rotor hubs were sectioned and evaluated by the contractor and a third hub was evaluated by the Air Force Materials Laboratory. A fourth hub was diffusion bonded and shipped to Sikorsky Aircraft where it was machined and dynamically fatigue tested. The test data compared to forged hub

data indicates that there is no significant difference between the diffusion bonded hub and production forged hubs.

Other Air Force Materials Laboratory, Manufacturing Technology Programs included two programs for roll bonding titanium alloy structural sections. McDonnell-Douglas made T-shapes and a complex shape using a bar rolling mill to apply the pressure. North American Rockwell conducted a program and made an airfoil shape, "J" sections, "Z" sections, "L" sections, and a "Hat" section. These parts were made on a plate rolling mill.

The potentials of diffusion bonding were recognized for fabrication of jet engine components. A program was conducted by General Electric for the development of a diffusion bonding process for assembling hollow titanium compressor blades. A comprehensive evaluation for acceptable bonding parameters was conducted. Most significant results of the bonding parameter studies was the determination that to obtain 100% bonding a controlled deformation of approximately 2 percent upset is required regardless of thickness. (Reference 9) Also significant was the surface finish evaluation which showed that for finishes rougher than 32 RMS, higher deformations were required to obtain 100 percent bonding. In this program hollow compressor blades were made from sheet plate, and bar stock rather than from forged halves (FIGURE 14) (Reference 10) Essentially the method consisted of

- a. Creep form airfoil shape
- b. Chem-Mill concave cavity
- c. Machine convex cavity
- d. Bond airfoil
- e. Bond dovetail blocks
- f. Finish machine

The diffusion bonded blades were tested to establish the integrity of a fabricated diffusion bonded airfoil by:

1. Ballistic impact
2. Bench fatigue

3. Whirligig fatigue
4. Stress deflection
5. Micro-examination

The test data from the diffusion bonded blades were compared with the GE4 (SST) hollow blades produced using forging procedures. Results on all the deflection tests indicate that finished blades produced by both methods have physically similar characteristics. On the GE4 (SST) engine a 175 pound per engine weight reduction was achieved by using hollow titanium compressor blades in stages 1 through 4. (Reference 10) The use of sheet, plate and bar stock for manufacture of hollow blades enabled substantial cost savings up to 50% over previous methods for manufacturing large hollow blades.

A program is currently being conducted at Pratt & Whitney for a diffusion bonded titanium alloy hollow fan disk. This contract is establishing a manufacturing method to produce hollow diffusion bonded titanium alloy fan disks from titanium 6Al-2Sn-4Zr-6Mo. Under this program the hollow rim of the disk will be produced by diffusion bonding. The hub and spacer will be made integral with the disk by inertia bonding which is also a solid state joining process. The disk being fabricated and tested is the first stage fan disk of the TF-33P7 engine.

Another method of diffusion bonding is based on the concept of conventional resistance spot or seam welding using resistance welding equipment. Under an AFML program at Solar, San Diego, a continuous seam diffusion bonding machine was constructed. The machine is based on a resistance welder modified, and includes a closed loop control for pressure and temperature. (Reference 11) Bonding of titanium and its alloys was demonstrated with the manufacture of single and double web I beams, rib reinforced panels, box beams and other shapes. Joint quality of I beams were evaluated by tensile tests, end compression tests, four point loading bend tests and fatigue tests. This continuous seam bonding technique has advanced to the extent that it is currently being used in advanced systems application. A titanium vane is being

CSDB bonded for Pratt & Whitney and engine seals from Hastelloy X are being fabricated for the CF6 engine at General Electric.

(Figures 15 and 16)

Diffusion bonding is intended for extensive use on the B1 program at North American-Rockwell. A large number of components have been identified and North American's press bonding capability will be utilized.

There is continued concern over the nondestructive inspection of diffusion bonded parts. The major concern is whether or not ultrasonic testing methods or any other nondestructive testing techniques are good enough to assure a sound product especially with reference to unbonded or partially bonded areas. This condition dictates that there must be precise control of the diffusion bonding process. Cleanliness of parts is critical and bears emphasis, control of the amount of deformation is critical during the bonding cycle. Metallographic sectioning and mechanical testing will continually be required over a sampling plan to assure reproducible acceptable quality.

INERTIA WELDING

Inertia welding is a process where one workpiece is fixed in a stationary holding device and the other workpiece is clamped in a spindle chuck with attached flywheel. The flywheel is accelerated to a predetermined speed, driving power is cut and the rotating part is thrust against the fixed piece. Friction between the parts decelerates the flywheel converting stored energy to frictional heat and a solid state joint results. Under a manufacturing technology contract at General Electric inertia welding was established as an improved method of jet engine compressor manufacture and demonstrated by the fabrication of TF39 stages 14-16 of the compressor rotor spool. One of the TF39 stages 14-16 compressor rotor was finish machined. Reduced machining costs and overall component weight reduction are significant benefits. Based on the mechanical properties data evolved in the TF39 stages 14-16 and the tolerances attainable for rotor spools General Electric has

committed the inertia welding process for use in fabrication of compressor rotors for the B1 engine.

In the contract at General Electric welding parameters were developed for Inconel 718 cross rolled plate. (Reference 12) With an established flywheel size there are only two parameters to control, namely, thrust and surface speed. Once correct weld conditions have been established based on mechanical property tests, micro-examination and visual examination of the size and nature of the flash, and nondestructive inspections, the amount of weld upset by length reduction of the weldment can be the basic process control technique. The process being automatic is intrinsically very reproducible. A statistical test plan was used to arrive at welding parameters for the Inconel 718. One inch outside diameter by 0.100 and 0.200 inch wall cylinders were specimen sizes used. Statistical analysis of the test data showed that the flywheel moment of inertia had little influence on the amount of upset or weld quality. Rotors were experimentally fabricated from both Inconel 718 plate which had been cold flanged to provide outside edge preparation and from Inconel 718 forged disks. Rotors made from plate stock were found to contain cracks after machining. While the cause of the cracking was not conclusively determined, it is believed that the following were all contributing factors:

1. Excessive grain size of cross-rolled plate
2. Improper machining of weld flash
3. Improper acid etch cleaning

All of these factors can be controlled or modified, and, therefore, the cracking should be preventable.

Sound experimental rotors were made from forged disks. Since previous metallographic studies had shown the presence of liquated phases in Inconel 718 inertia welds made at high angular velocities, the flywheel moment of inertia was increased from 26,038 to 32,500 lb-sq ft, thereby allowing some reduction in welding speed. Three sets of 24-in. dia. test rings welded in the wall thickness-diameter study

were cut apart and remachined for additional test piece welds.

Welding of the three ring sets and test disks from two forgings showed no significant changes in the welding parameters, maximum input energy and welding pressure, from those used for cross-rolled plate. The two rotor welds were then made with good dimensional and upset results.

The rotor was machined and then aged in vacuum using controlled heating and cooling rates of 200 F/hr to reduce any possibility of warpage or distortion of the nearly finished machine rotor. The standard Inconel 718 aging cycle of 8 hr at 1325 F + 8 hr at 1150 F was used. Dimensional inspection after aging showed that no significant changes or distortion had occurred, and zygo inspection showed no defect indications. The finished machined rotor is shown in Figure 17.

Inertia welding was one of several processes evaluated under an Air Force sponsored program at Pratt & Whitney Aircraft for joining of bimetal shafts. The ideal low pressure turbine shaft would be made from two joined materials using an alloy with high fatigue and high yield strength at the cold end, and a material with high fatigue strength, high creep strength, and corrosion resistance at the hot end. (Reference 13) Such a bimetal shaft would be lighter in weight, and, with no cooling requirement, the complexity of the cooling air system would be effectively reduced. In this particular program the coextrusion process was selected for joining the bimetal shafts. For the AMS 6304 steel to Inconel 718 bimetal combination it was determined that a value of 130 KSI in tension at room temperature was assigned as the acceptance level at the joint. This value was expected to provide a joint suitable for engine operating conditions. The results of test specimens in tension and shear showed that coextrusion was the best method for making bimetal shafts in the materials combination selected. The coextrusion process produces a metallurgical bond between the two materials being joined by forcing the materials through an extrusion die at an elevated temperature and reducing the cross sectional area. (Figure 18)

The finished shaft was assembled into a TF30-P-3 engine which was run in a 150 hour endurance test. The test consisted of 25 six hour cycles. (Figure 19) Though test specimens in this program showed lower fatigue strength than the coextruded joints it is believed that the inertia welding process offers considerable potential for joining bimetal shafts. It is felt that by changing joint designs and material combinations the inertia weld can be shown to possess mechanical properties, including torsional fatigue strength equal to coextruded joints. It is expected that inertia welded shafts would be considerably more cost effective because of reduced steps in processing to the finished condition.

Cherrybuck ® fasteners produced by the Cherry Rivet Division of Townsend, Santa Ana, California, produces bimetal solid titanium fasteners by inertia welding. The fastener is made from Ti 6Al-4V inertia bonded to a commercially pure ductile tail. (Reference 14)

WELDBOND

This process represents the marriage suggested in the title of this paper. The process uses resistance welding in complement with adhesive bonding. Most of the work conducted thus far has been resistance spot welding through the adhesive. In process application the force of the electrodes moves the adhesive from the spot weld so a resistance weld nugget is formed with adhesive surrounding the nugget and covering the remainder of the faying surface.

Lockheed-Georgia began experimental process studies of resistance welding through high strength adhesives in the mid 1960's. Extensive static, axial load fatigue, and sonic testing produced weldbonded structures superior both in strength and in weight advantage to those joined by high strength tapered fasteners. Preliminary cost studies indicated that the automatic weldbonding process would result in a large cost savings in the total production process. In July 1969 the Air Force Materials Laboratory, Manufacturing Technology Division, awarded a contract to Lockheed-Georgia for fabrication of a full scale

fuselage barrel section by the resistance spot weld-adhesive bonding process. A full scale fuselage barrel section 85 inches in diameter by 120 inches long from 2024 and 7075 aluminum alloys, was fabricated during the program. (Reference 15 - Figure 22)

Actual joining of parts using a combination of resistance spot welds and adhesive is relatively straight forward. To begin with most of the processing steps involved in resistance spot welding are applicable to weldbonding. The parts are chemically cleaned as for spot welding, wrapped and stored up to 36 hours if required, and removed for welding.

The paste adhesive is applied to the parts. The parts are then brought together and temporarily clamped. The parts are then placed between the electrodes of a conventional three phase, variable pressure type spot welder and are welded together. After welding the structure is placed in a low temperature oven and the adhesive is cured for approximately one hour. Time and temperature is dependent on the type adhesive used and the alloy being weldbonded.

The fuselage barrel section was subjected to upbending, downbending, and torsional loads to the C140 test spectrum. These loads represented limit loads sustained by the fuselage. Figure 23 shows the fuselage at maximum torque. Note the shear buckles that were produced during this loading. Thick buckling demonstrated that the weldbond joints were highly stressed during the static loading sequence. Subsequent to the torque load the fuselage was subjected to pressure cycling with the pressure ranging from 1 PSI to 12 PSIG (1 cycle being equivalent to 1 flight pressurization). The fuselage was subjected to 48,000 cycles which is approximately 4 lifetimes of an aircraft before failure occurred. The failure was a three (3) foot long tear through mechanical fasteners. This test dramatically demonstrated the improved strength of the weldbonded structure when compared with the mechanically fastened joint.

Fabrication and test of the fuselage barrel section confirmed and substantiated data obtained during earlier development of the weldbonding process. Some of these data are as follows:

1. Radiographically clear spot welds could be consistently obtained when welding through paste adhesive.
2. High quality welds could be made in high strength aluminum alloy up to 72 hours after layup of the parts with adhesives at the parts interface.
3. Axial load fatigue endurance had been increased many times over that of mechanical fasteners. (Figure 20)
4. Joint static strength of weldbond was superior to all other joints tested. (Figure 21)

The weldbond process offers the potential of significantly lower manufacturing costs. The work performed at Lockheed-Georgia Company indicates that the cost of a weldbonded fuselage structure is 25 to 50% of the cost of a riveted assembly. Similar cost savings are anticipated in other applications.

Currently in progress at Lockheed-Georgia is a weldbond program sponsored jointly by the Air Force Materials Laboratory and Air Force Flight Dynamics Laboratory. This program will optimize the weldbond process for aluminum, generate structural design and engineering data, fabricate test specimens and full scale flight "hardware" for the C-130 aircraft. The fabricated aluminum component will be static and fatigue tested prior to installation of a panel section on the C-130. (Figure 24) A service test will be conducted with continued surveillance of performance over an extended time period.

A relatively small contract was AFML sponsored at Lockheed-Georgia to establish weldbond parameters for titanium. Titanium 6Al-4V in the solution treated condition in thicknesses of 0.045 and 0.063 inches was used in one series of tests. Titanium 6Al-4V in the annealed condition in thicknesses of 0.020" and 0.025 inches was used in other tests. The two better adhesives from several evaluated were 3M Company EC 3419 and 3M Company EC 2214 Hi-Flex. Realistic evaluation of weldbonded

joints in titanium required that wherever possible weldbond joint strength would be compared directly to strength of other type joints. Joints were designed utilizing spot welds only, mechanical fasteners only, mechanical fasteners with adhesive, and structural adhesive bond only. Joint configurations, joint overlap, and joint thicknesses were kept identical in order to obtain a direct strength comparison at room and elevated temperatures. Weld schedules were established using MIL SPEC W-6858-C as a baseline reference. From the tensile tests conducted for each comparative process the weldbond joints show a superior strength at room temperature in all types tested. Weldbond joints were produced that were consistently stronger than those of either mechanical fasteners, structural adhesive bonds, or mechanical fasteners with adhesive at the joint interface. The combined peel strength of spot welds and adhesive bond joints was approximately five times greater than that of a bond joint alone. Detailed test data are included in the paper entitled "Development of the Weldbond Process for Joining Titanium." (Reference 16) to be included in the publications from this symposium.

Lockheed Missiles & Space Company, Sunnyvale, California, has conducted extensive work with the weldbond process. Their work is covered in the paper entitled "Weldbonding Sheetmetal Structures" and will be included in the published articles from this symposium. (Reference 17) They have conducted work for evaluation of weldbond for large propellant tanks at cryogenic temperatures. Lockheed-Sunnyvale has also developed the process for spacecraft shroud applications using a resistance wheel electrode concept. This type of application is a corrugation to flat face sheet design. In the previous design the corrugated panel was attached to the face sheet by rivets. The use of weldbond in place of rivets will produce a panel which is far stronger and less costly to make.

NASA, Manned Spacecraft Center, Orbiter Procurement Center, Houston, recently awarded a contract to Lockheed-Sunnyvale entitled "Weldbond Development Program for Space Shuttle Application." This program will lead to the application of weldbonding to cryogenic pressure vessels (LH₂ and LO₂, temperature range + 300°F to -423°F), atmospheric gas

containers (crew cabin), and in general to space structures.

Sikorsky Aircraft Division of United Aircraft Corporation has used a significant amount of weldbond on their S67-Blackhawk helicopter particularly in the tail cone section.

Weldbond is also being evaluated for use in rail car bodies, trailer truck bodies, and metal cabinets subject to high vibratory conditions.

The future of weldbond looms big. The improved properties of the process over competing processes and reduced manufacturing costs enhances its potential for extensive production application.

The foregoing discussion is but a summary of selected works with five specific joining processes. Since it is but a sampling of metals joining technology one can readily envision the interdisciplinary involvement, the magnitude of the metals joining area and the need for continued development of technology by industry and government.

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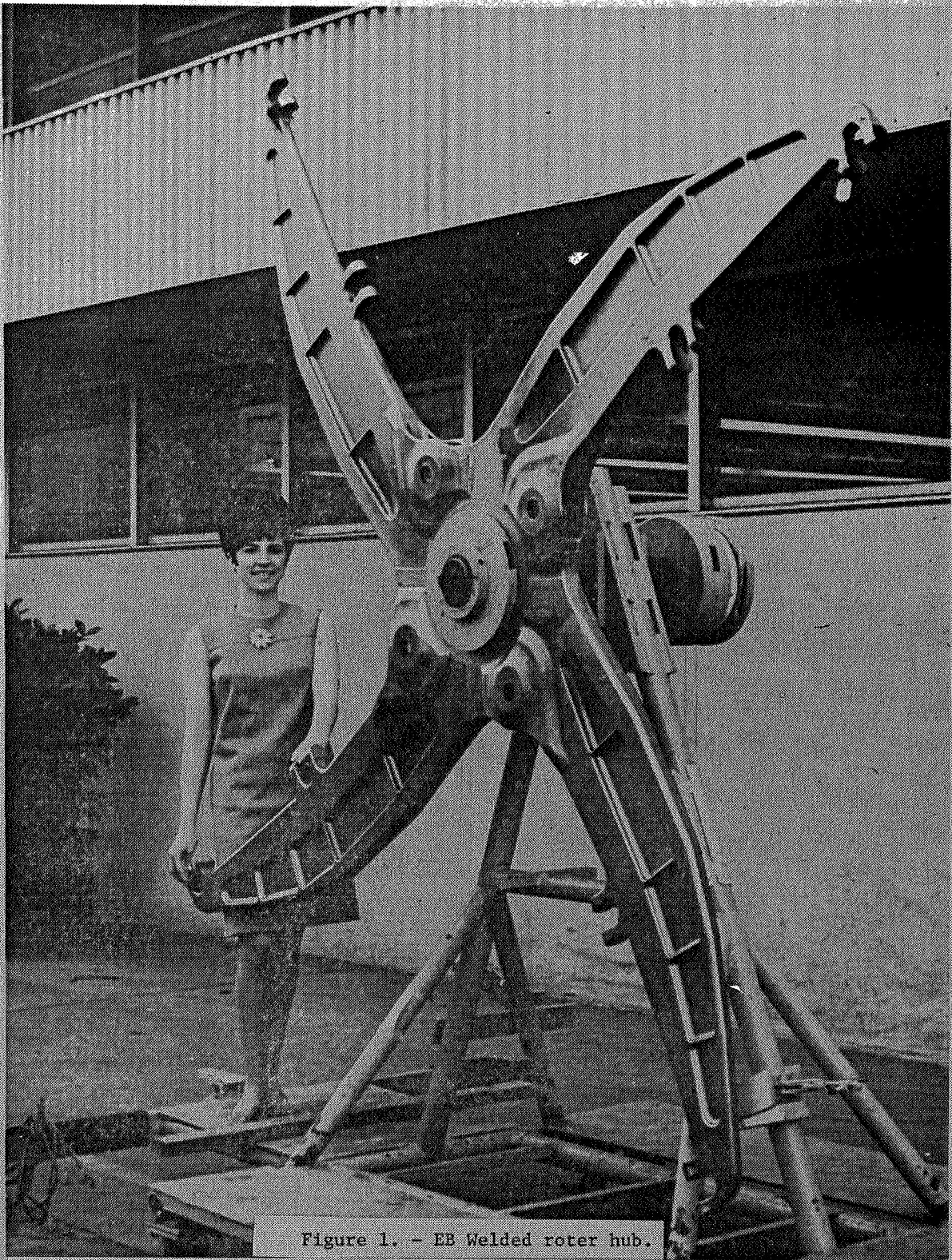


Figure 1. - EB Welded rotor hub.

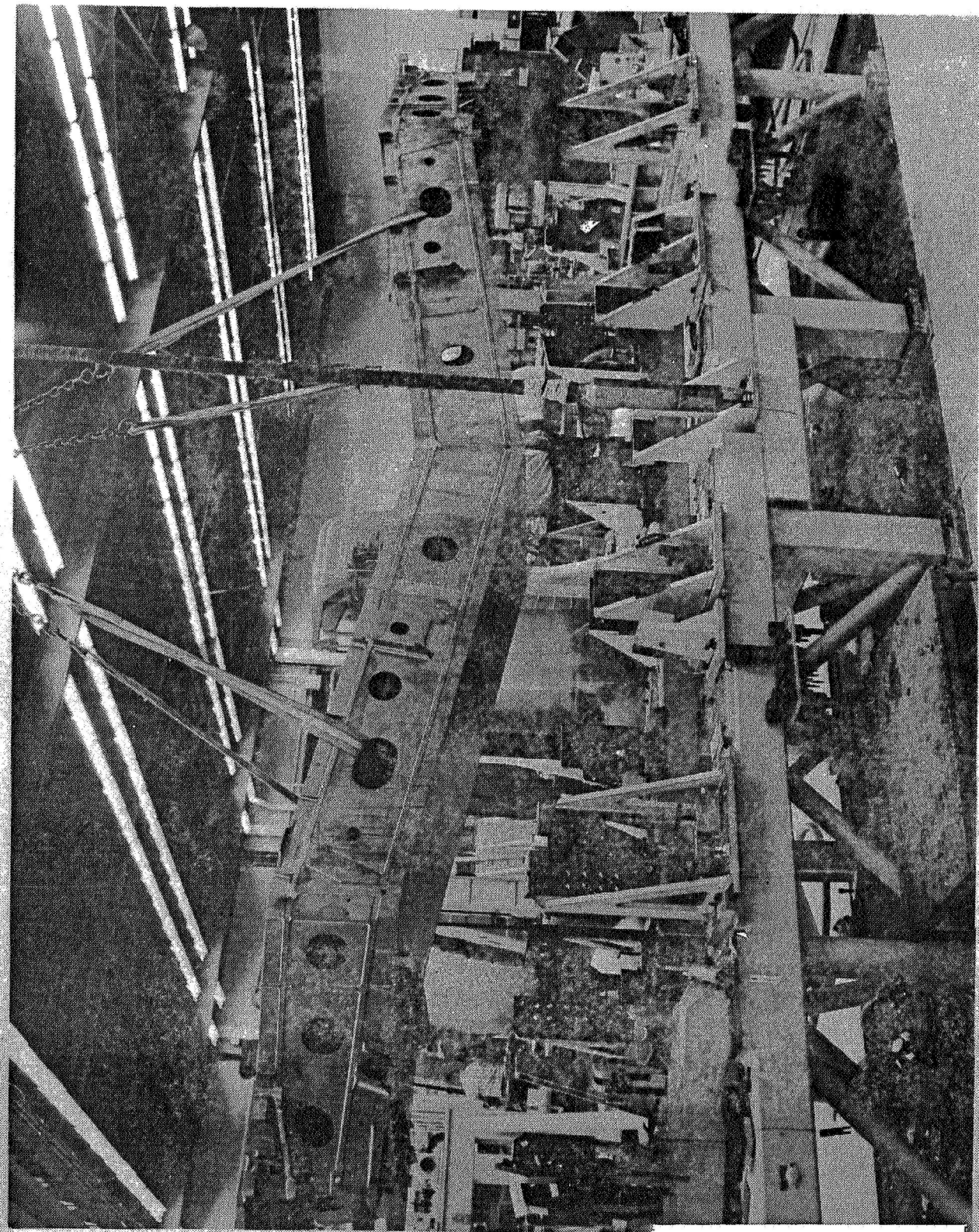


Figure 2: - EB welded F14 wing center box.

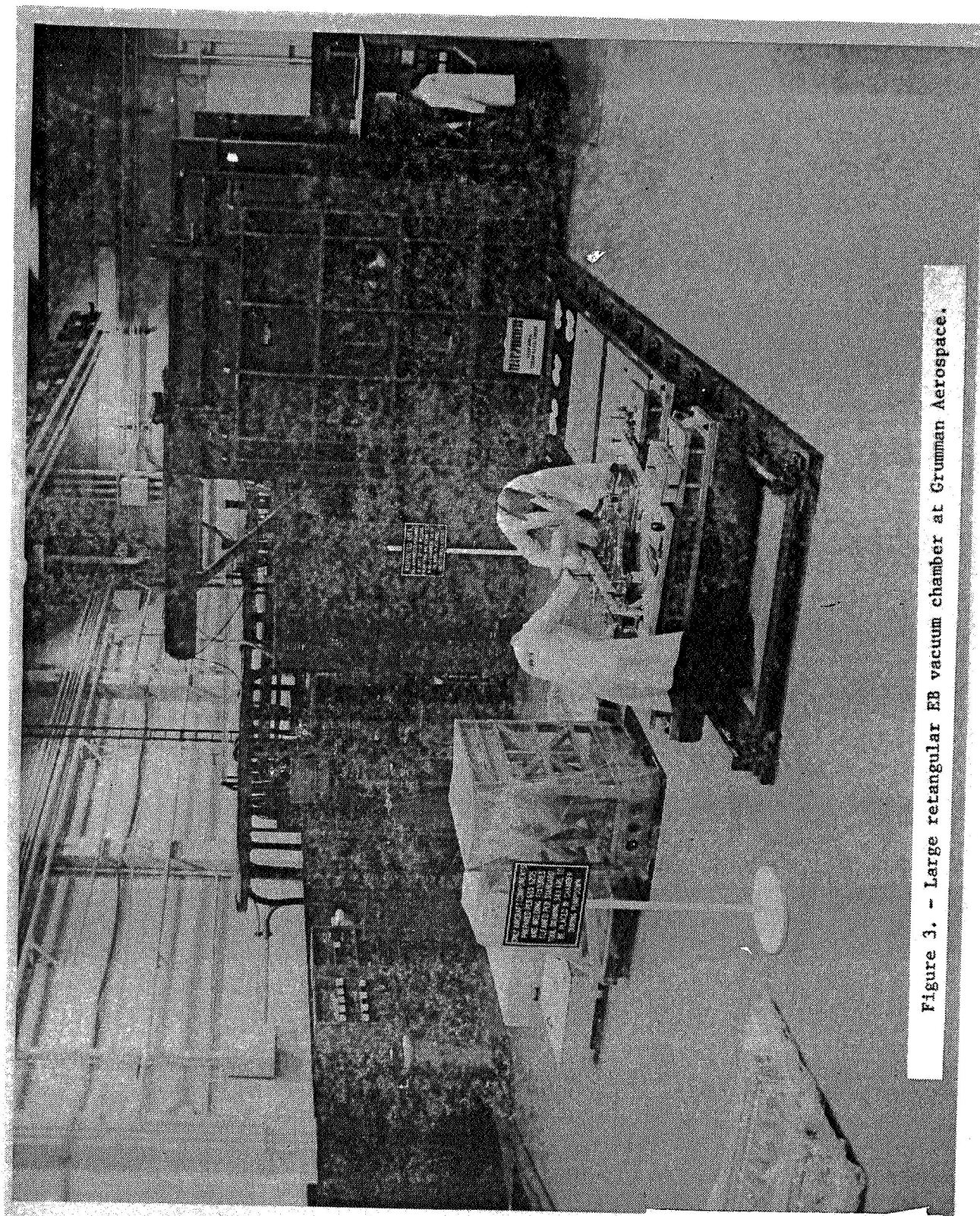


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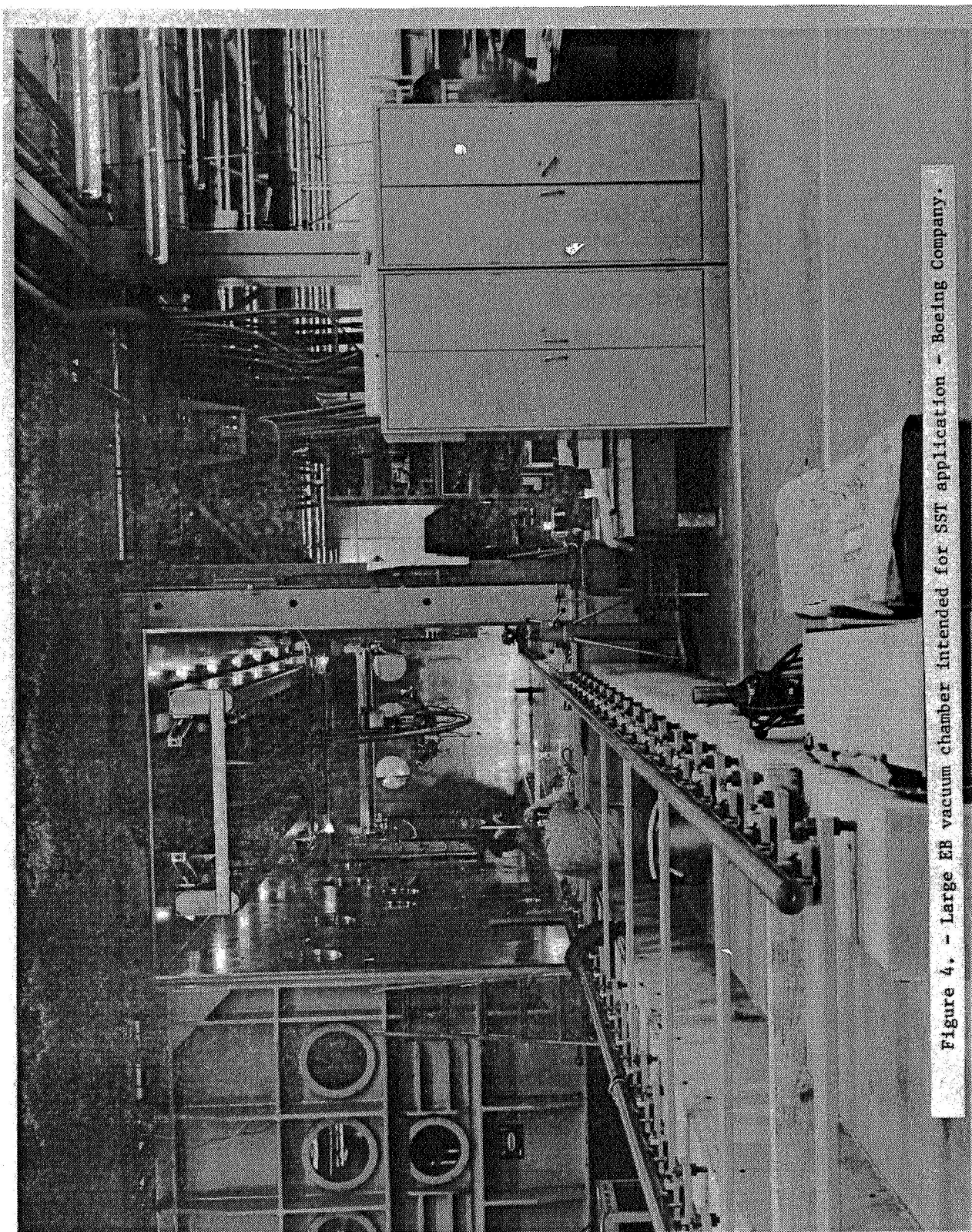


Figure 4. - Large EB vacuum chamber intended for SST application - Boeing Company.

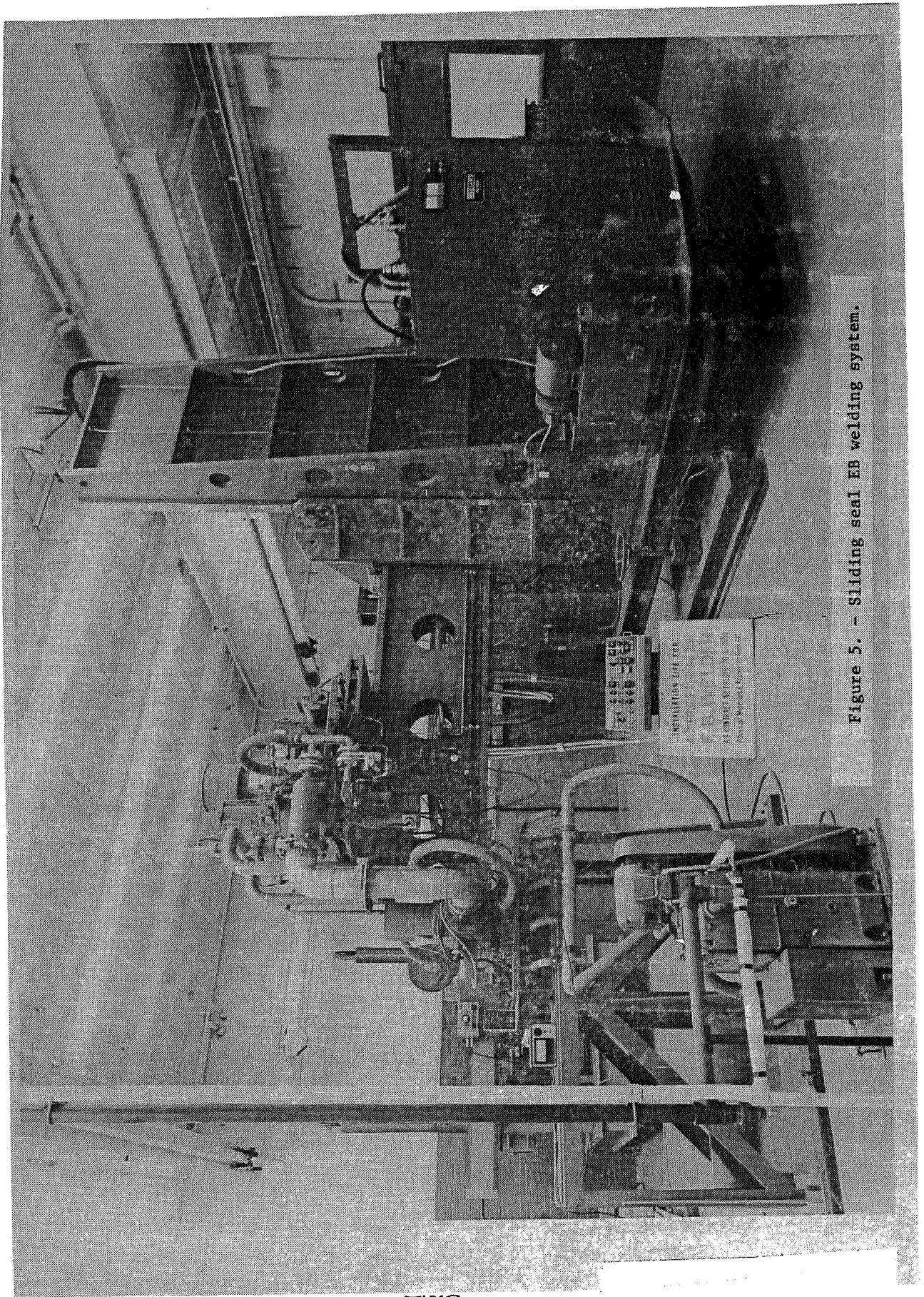


Figure 5. - Sliding seal EB welding system.

SLIDING SEAL EB EB WELDS

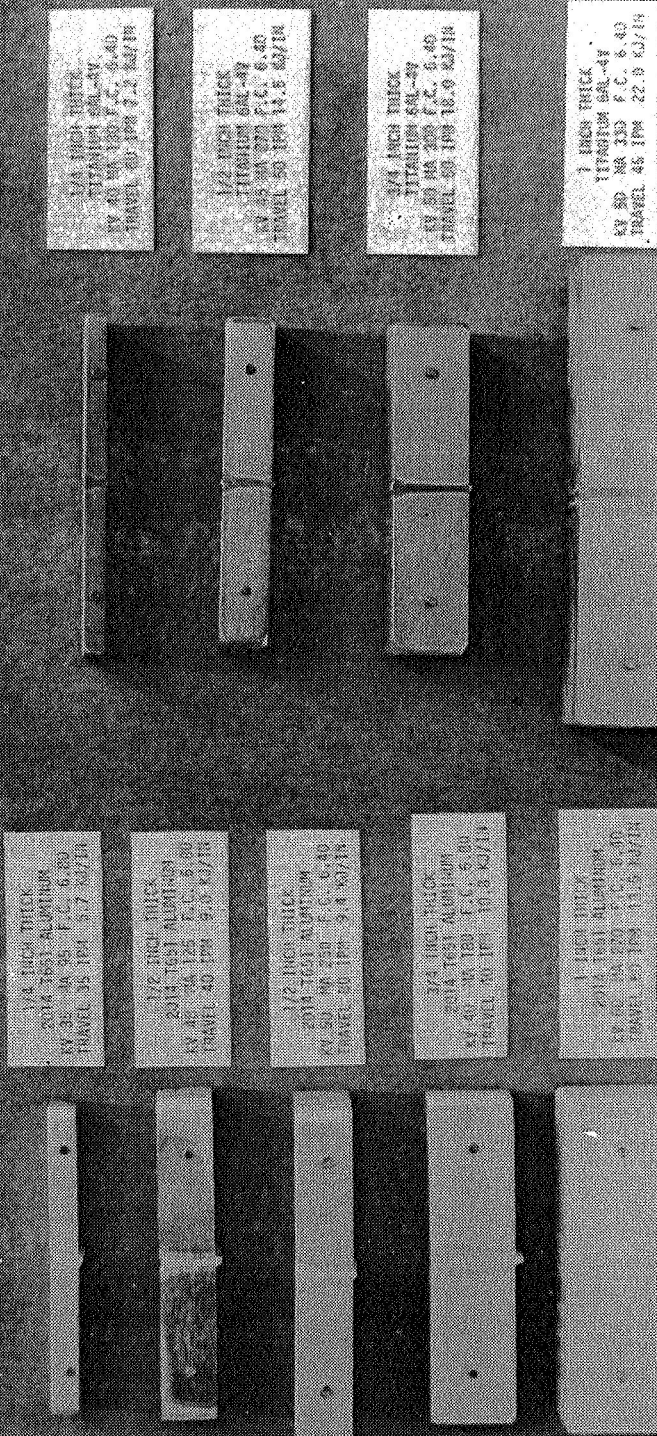


Figure 6. - Sliding seal electron beam welds.

TOTAL WELD TIME	QUALITY OF WELD	COST OF JOINT PREPARATION	DISTORTION
EB	EB	HOT WIRE	EB
PLASMA	PLASMA	PULSED	PLASMA
HOT WIRE	PULSED	PLASMA	PULSED
PULSED	HOT WIRE	EB	HOT WIRE

BEST
SELECTION

LESS
DESIRABLE

Figure 7. - Process selection based on welding several high strength alloys under AF contract at Bell Aerospace.

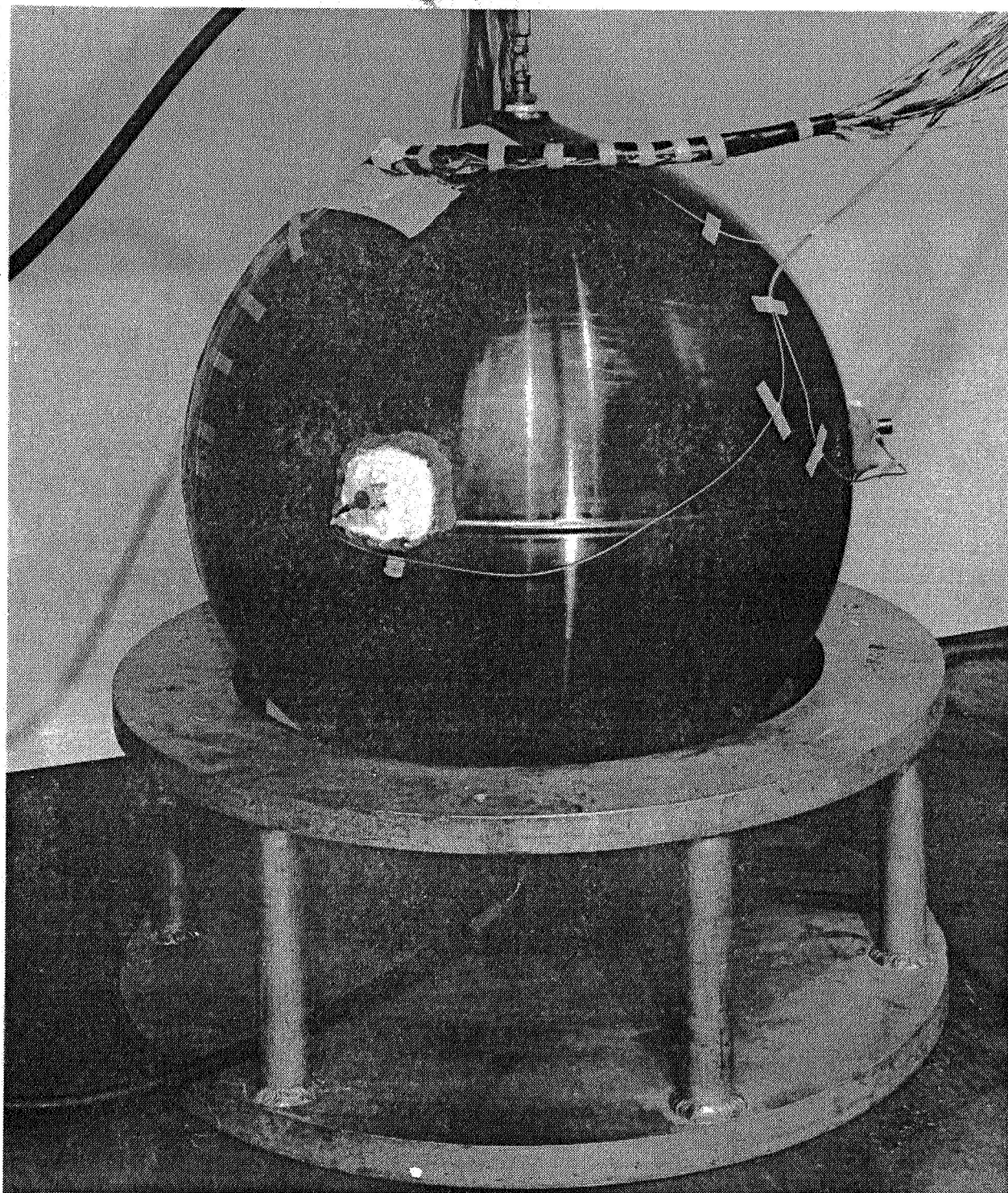


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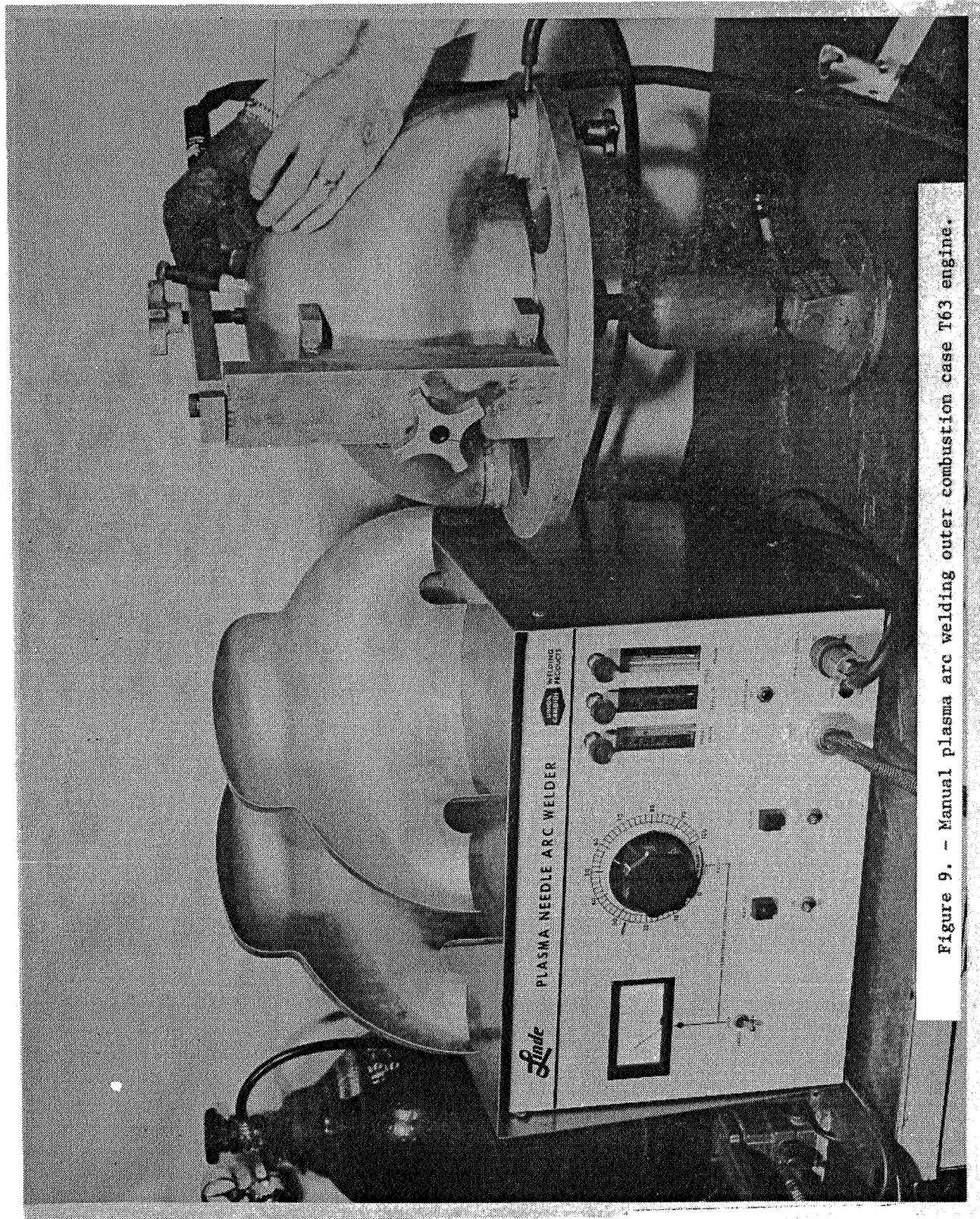


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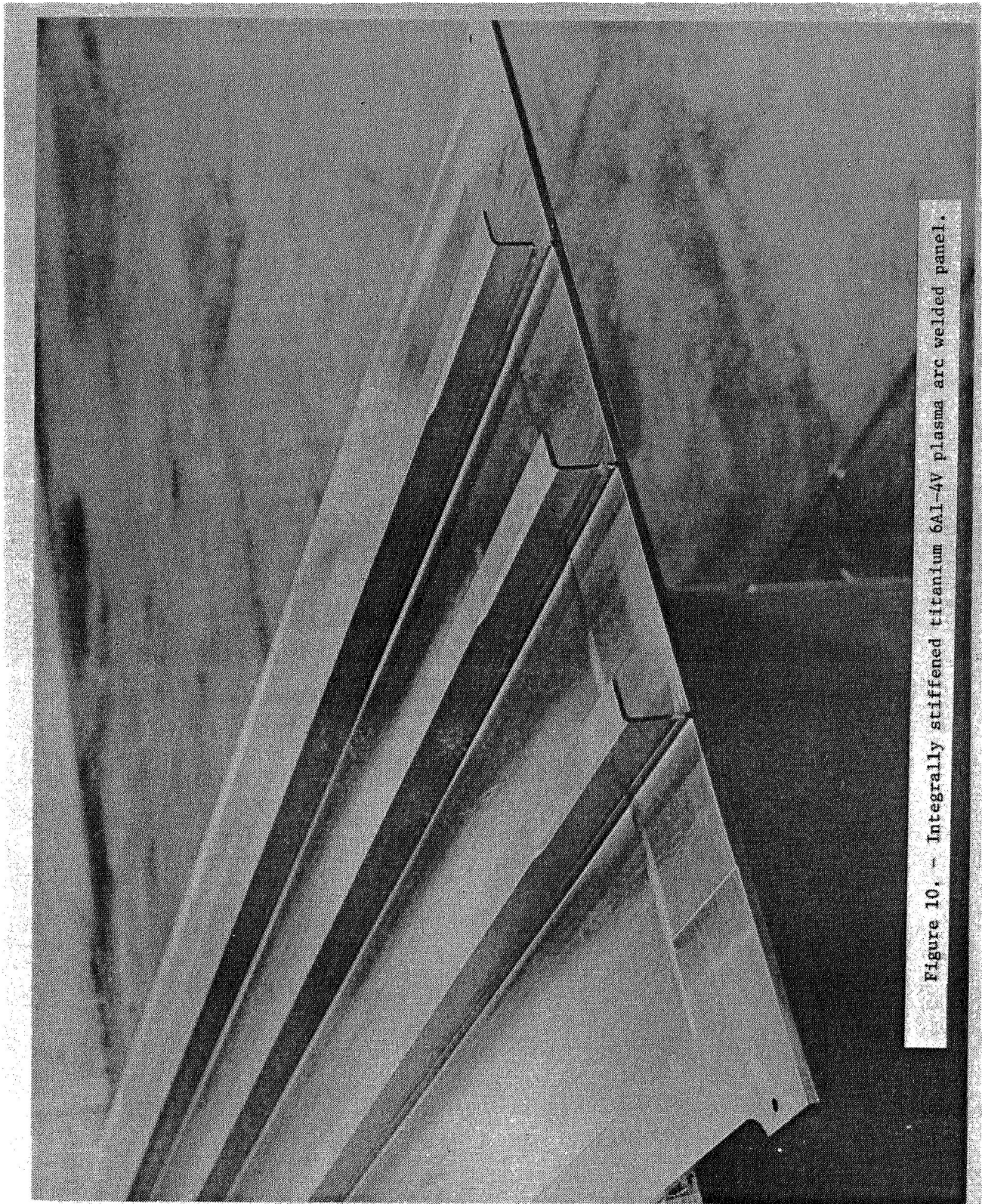


Figure 10. - Integrally stiffened titanium 6Al-4V plasma arc welded panel.

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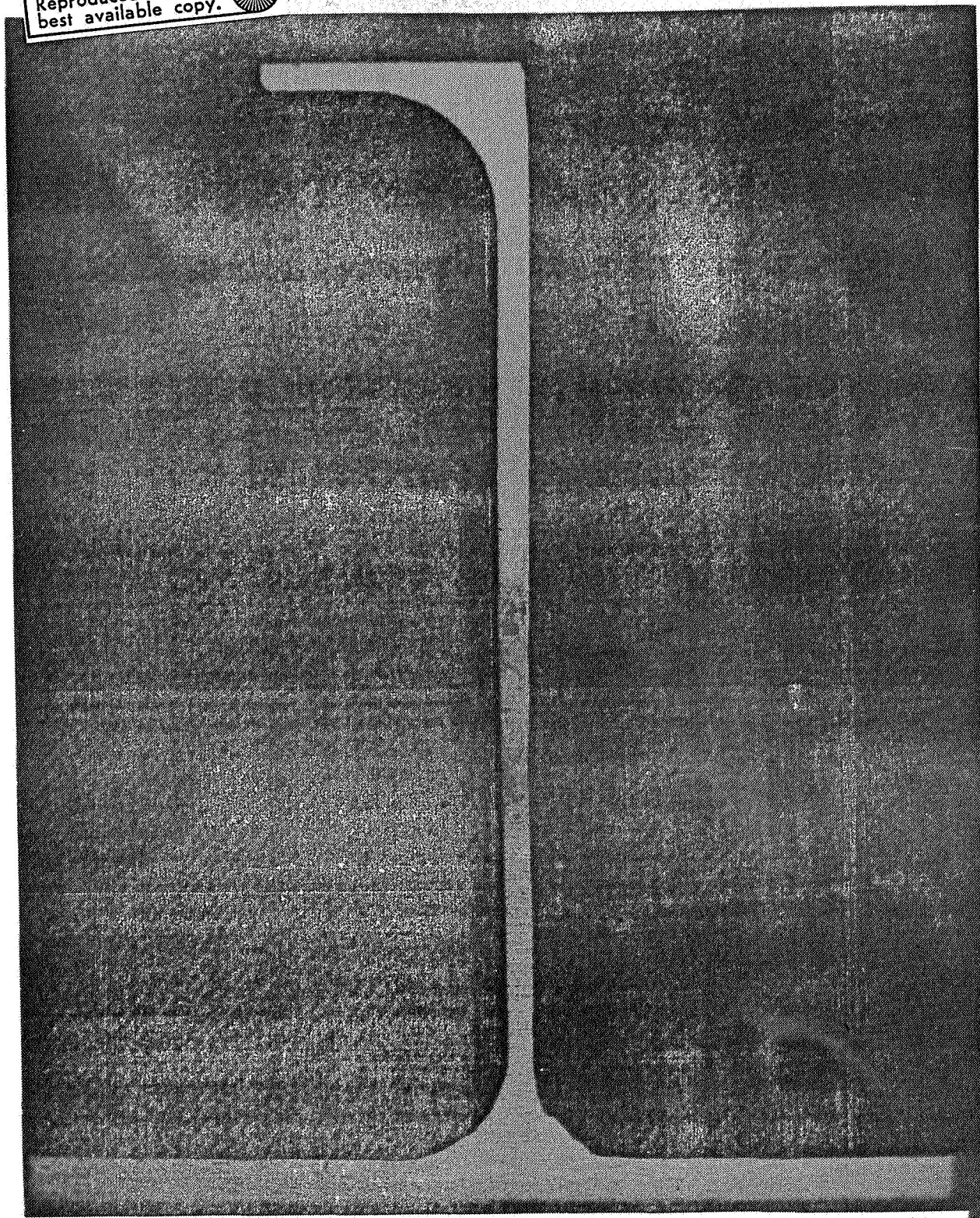


Figure 11. - Integrally stiffened titanium 6Al-4V cross section plasma arc weld microstructure.

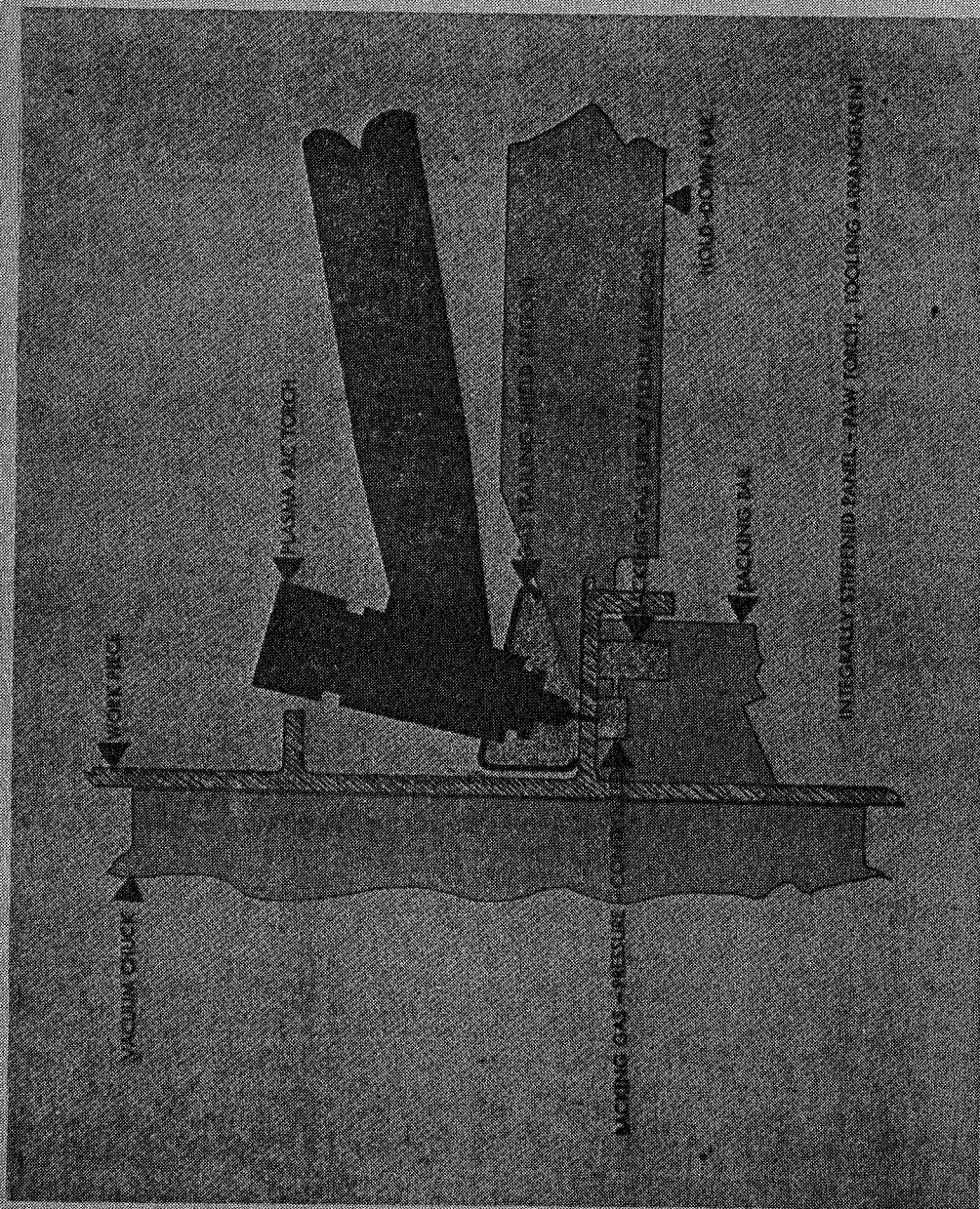


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BOEING

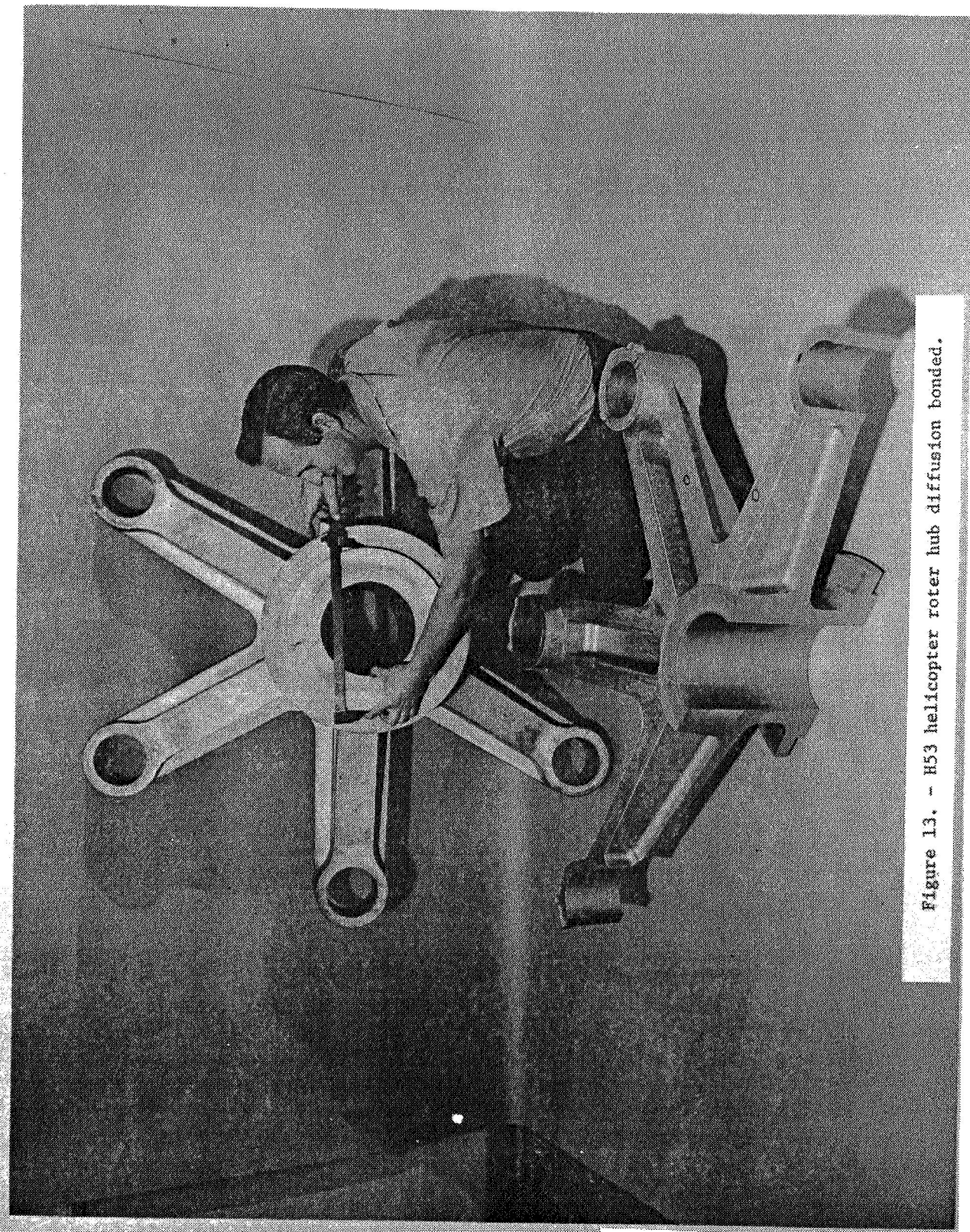


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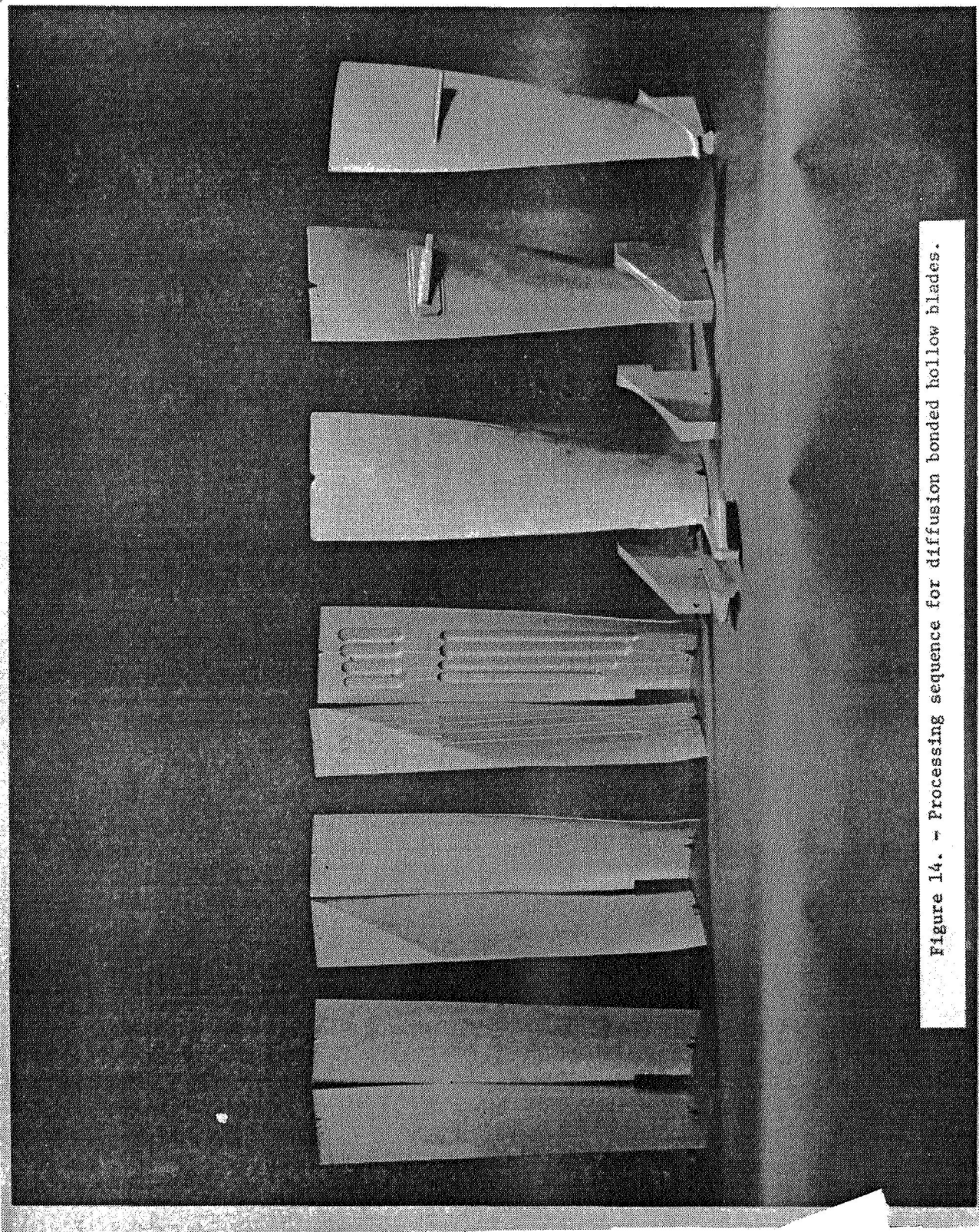


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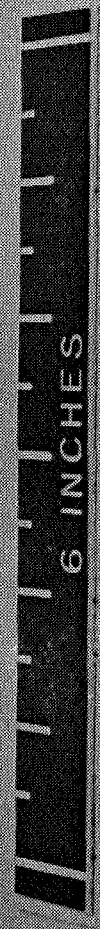
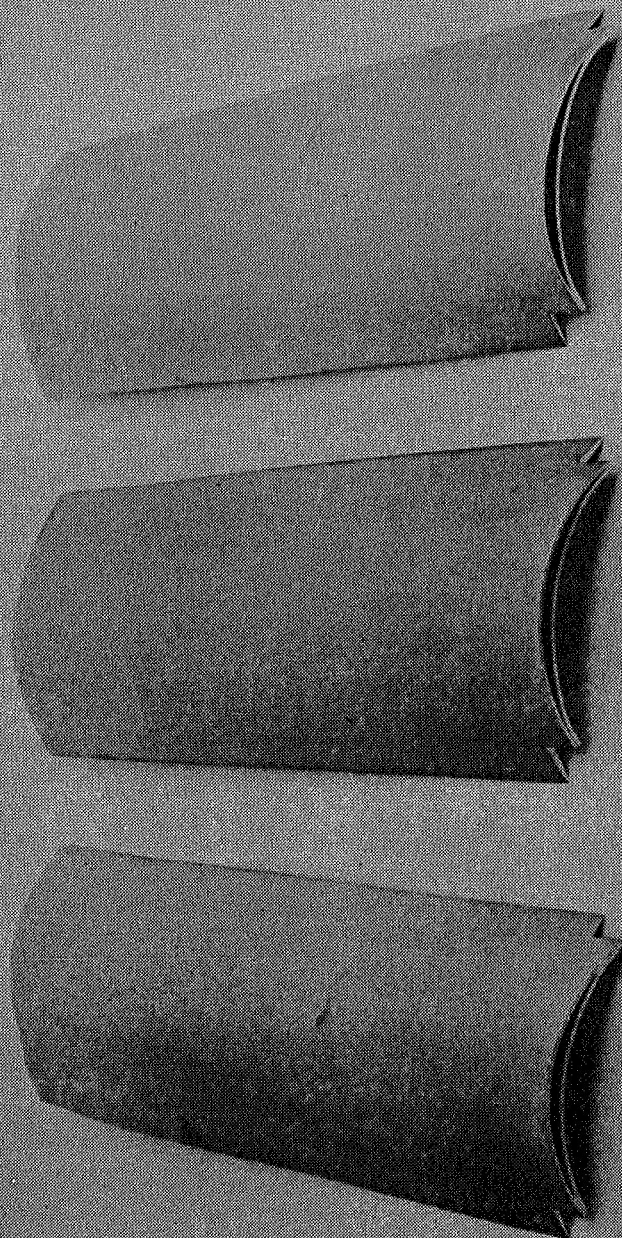


Figure 15. - Continuous seam diffusion bonded vane.

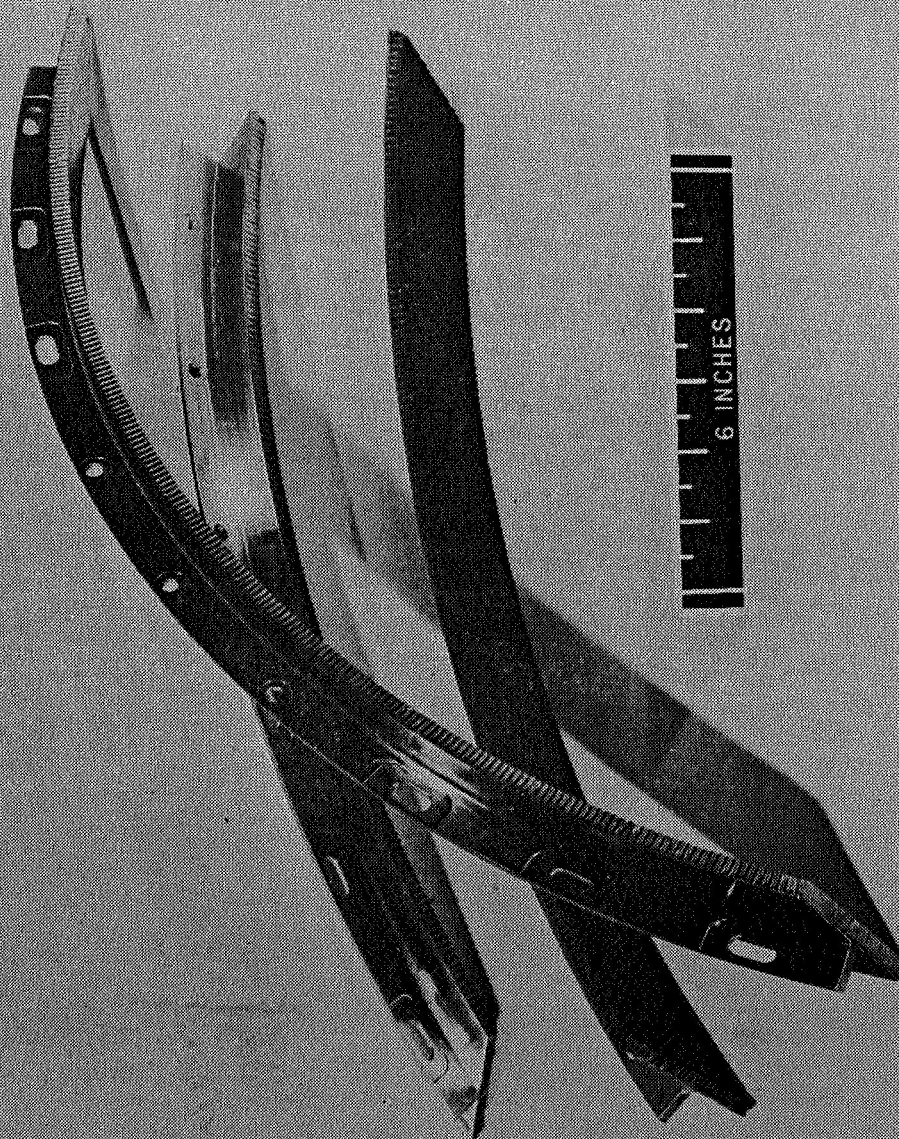
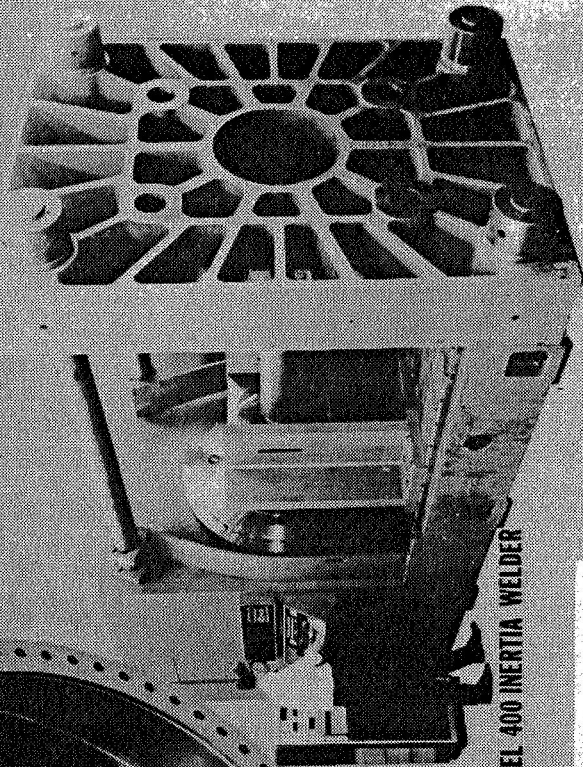
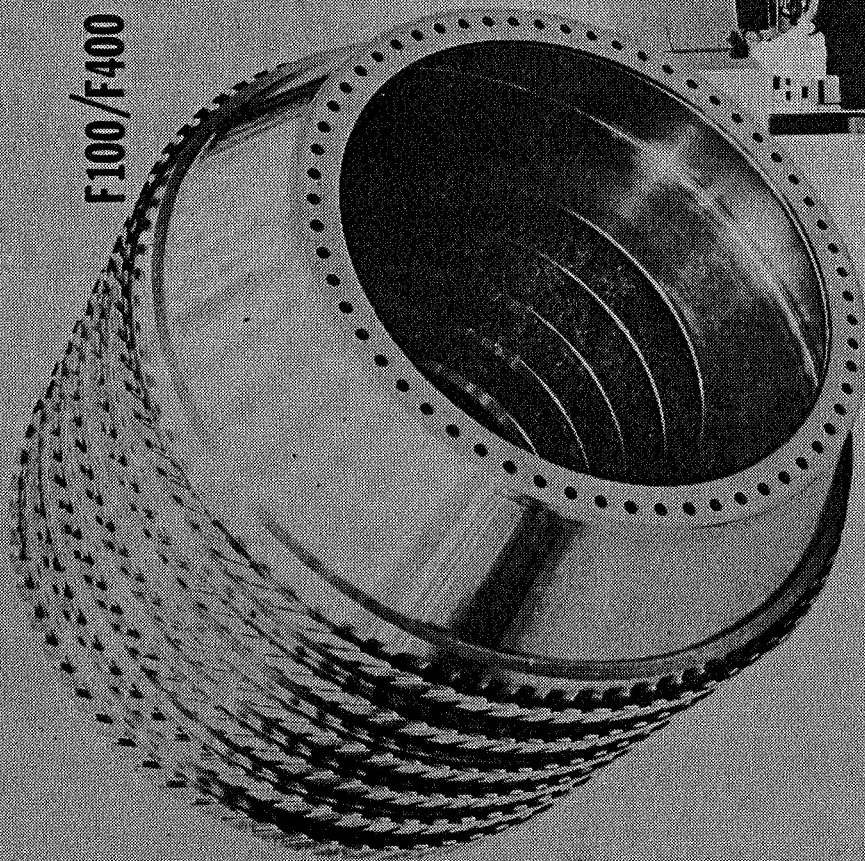


Figure 16. - Continuous seam diffusion bonded engine seals.

F100/F400 INERTIA WELDED ROTOR



MODEL 400 INERTIA WELDER

Figure 17. - Finish machined inertia welded rotor.

SCHEMATIC OF COEXTRUSION PROCESS

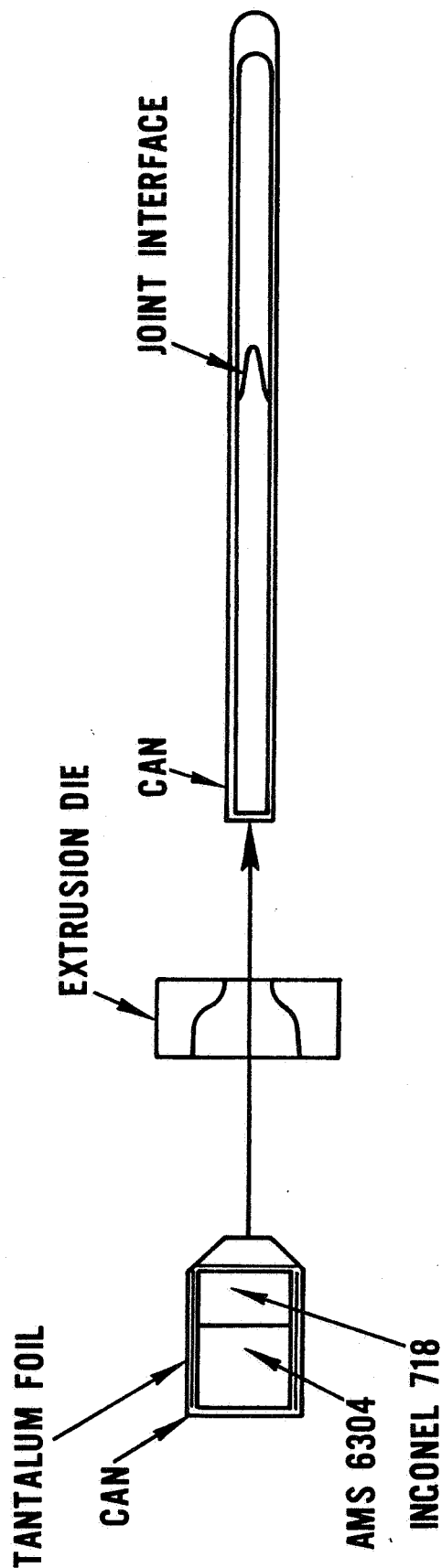


Figure 18. - Schematic of coextrusion process.

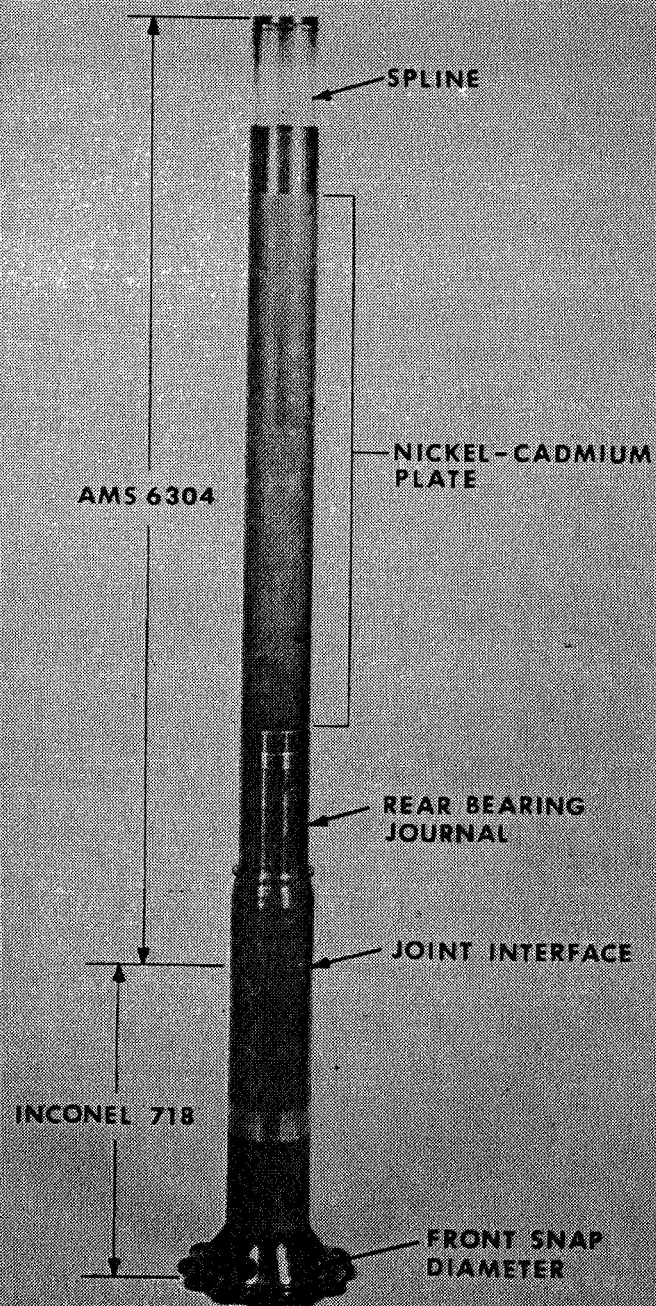


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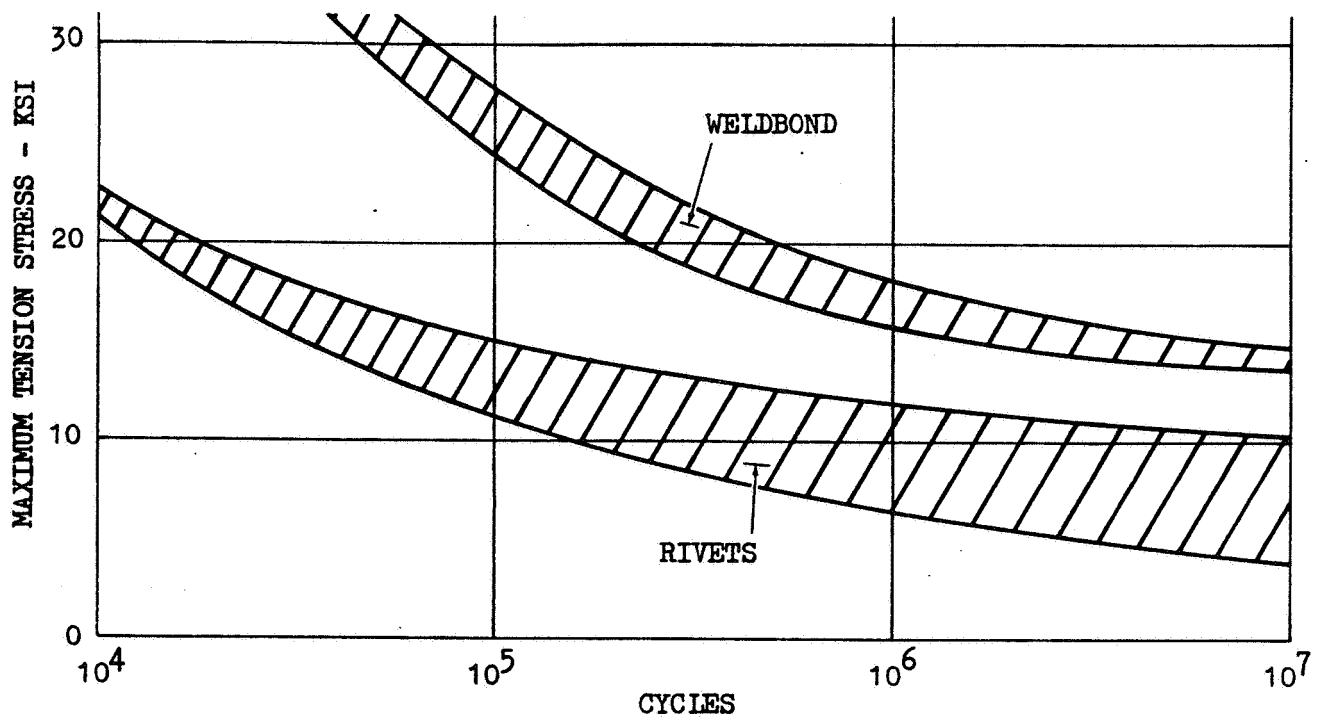


Figure 20. - Axial load fatigue strength of weld bond as compared to rivets.

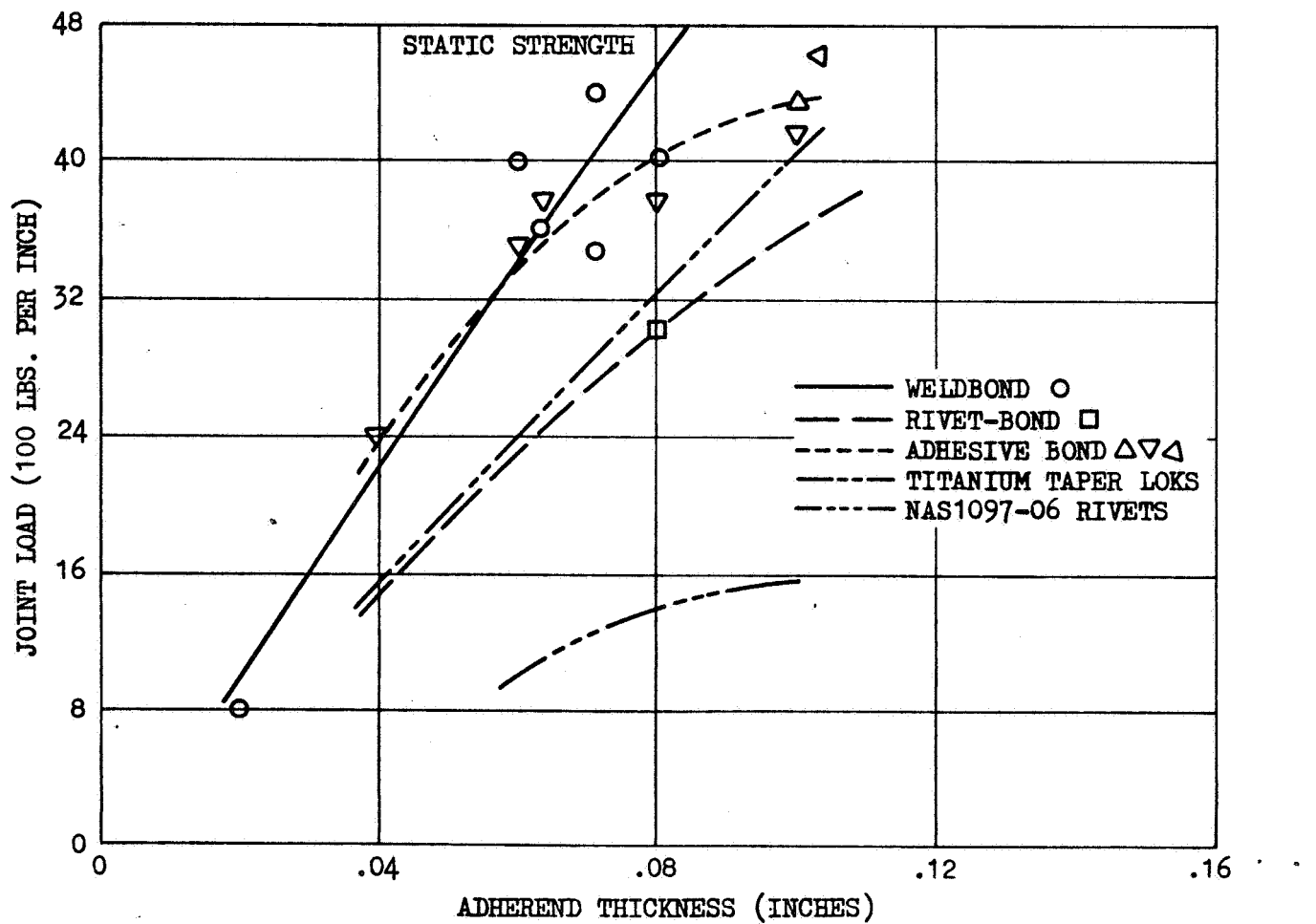


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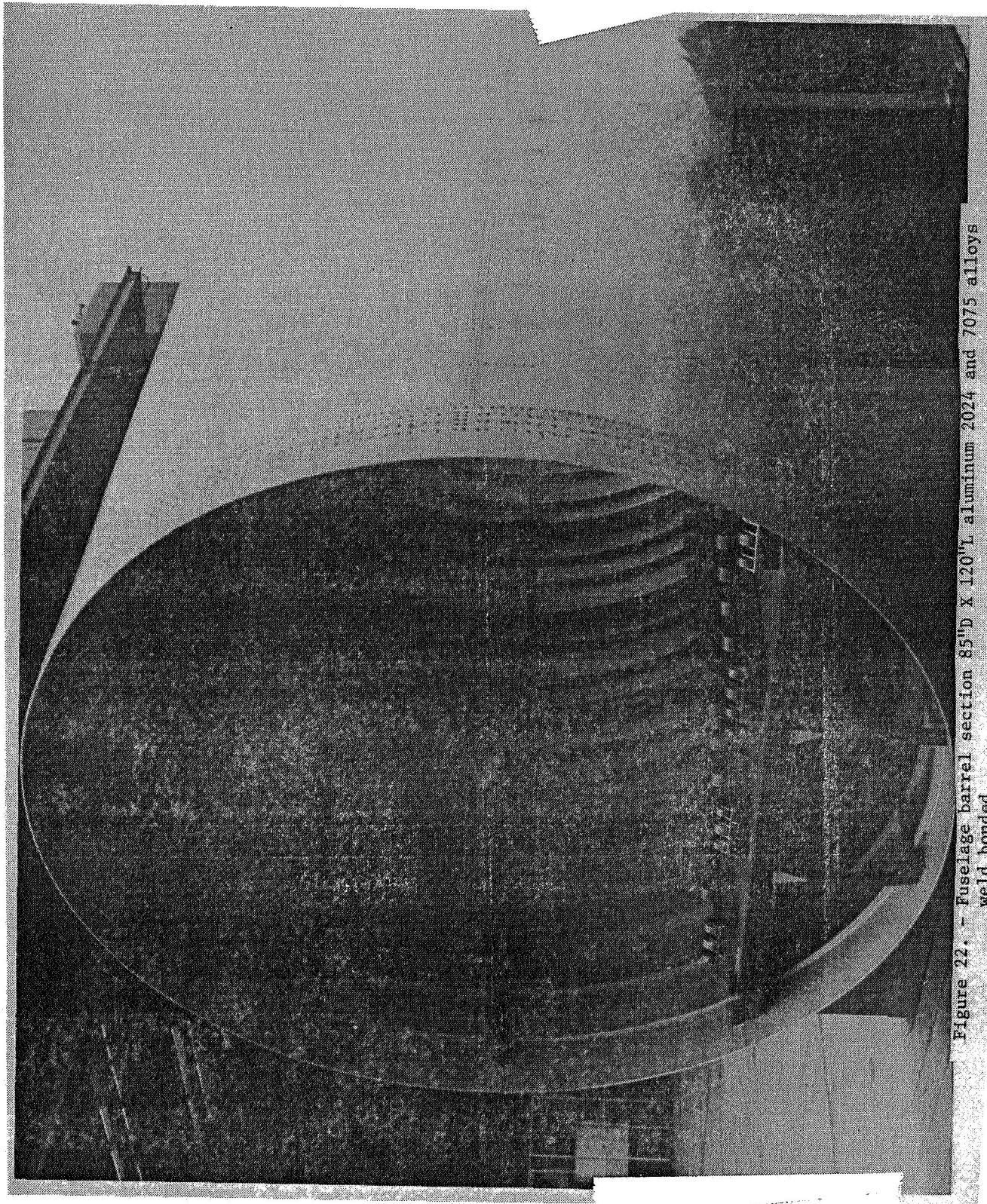


Figure 22. - Fuselage barrel section 85"p x 120"l aluminum 2024 and 7075 alloys weld bonded.



Figure 23

BARREL SECTION ELASTIC BUCKLING DUE TO TORSIONAL LOADING

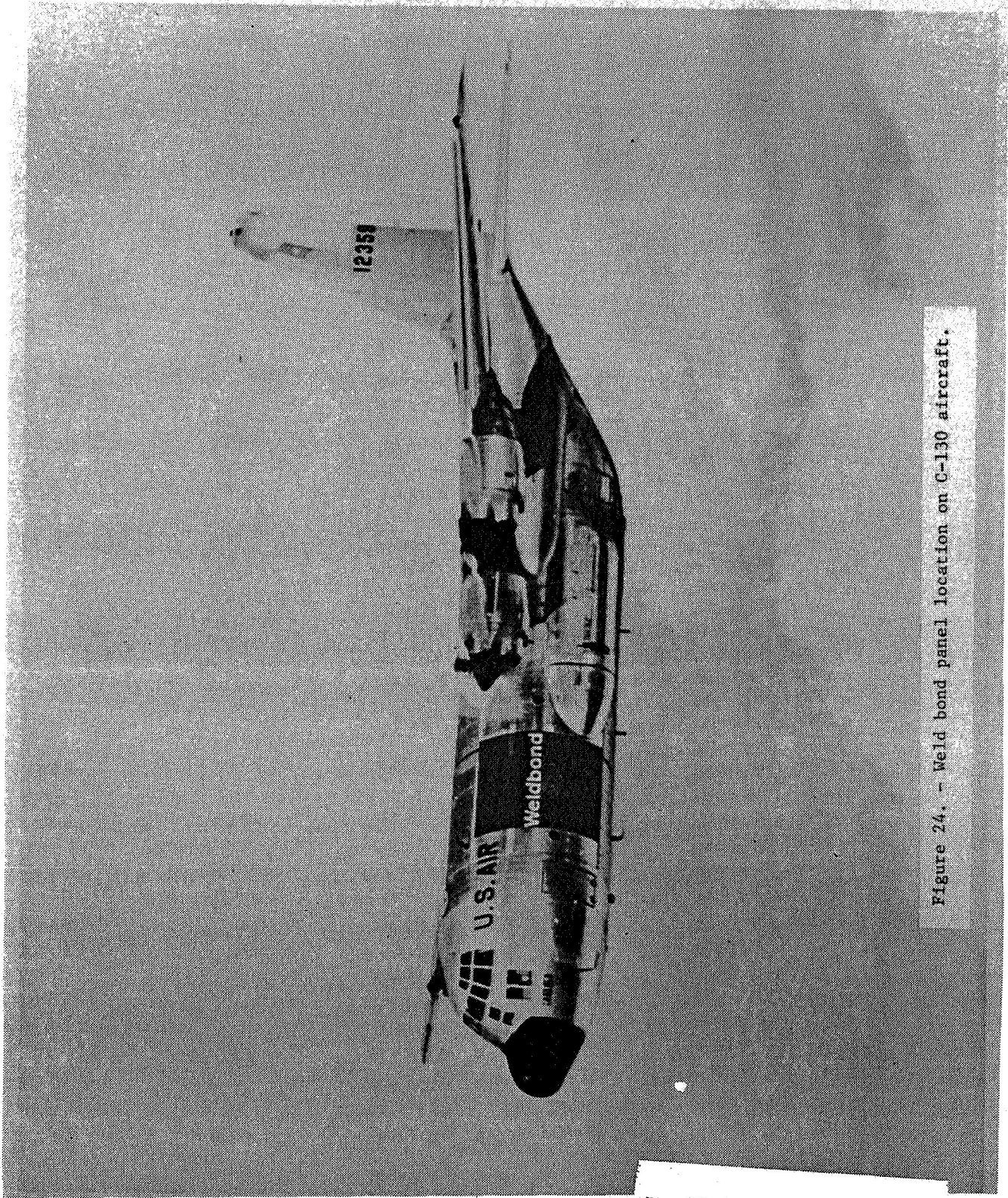


Figure 24. - Weld bond panel location on C-130 aircraft.